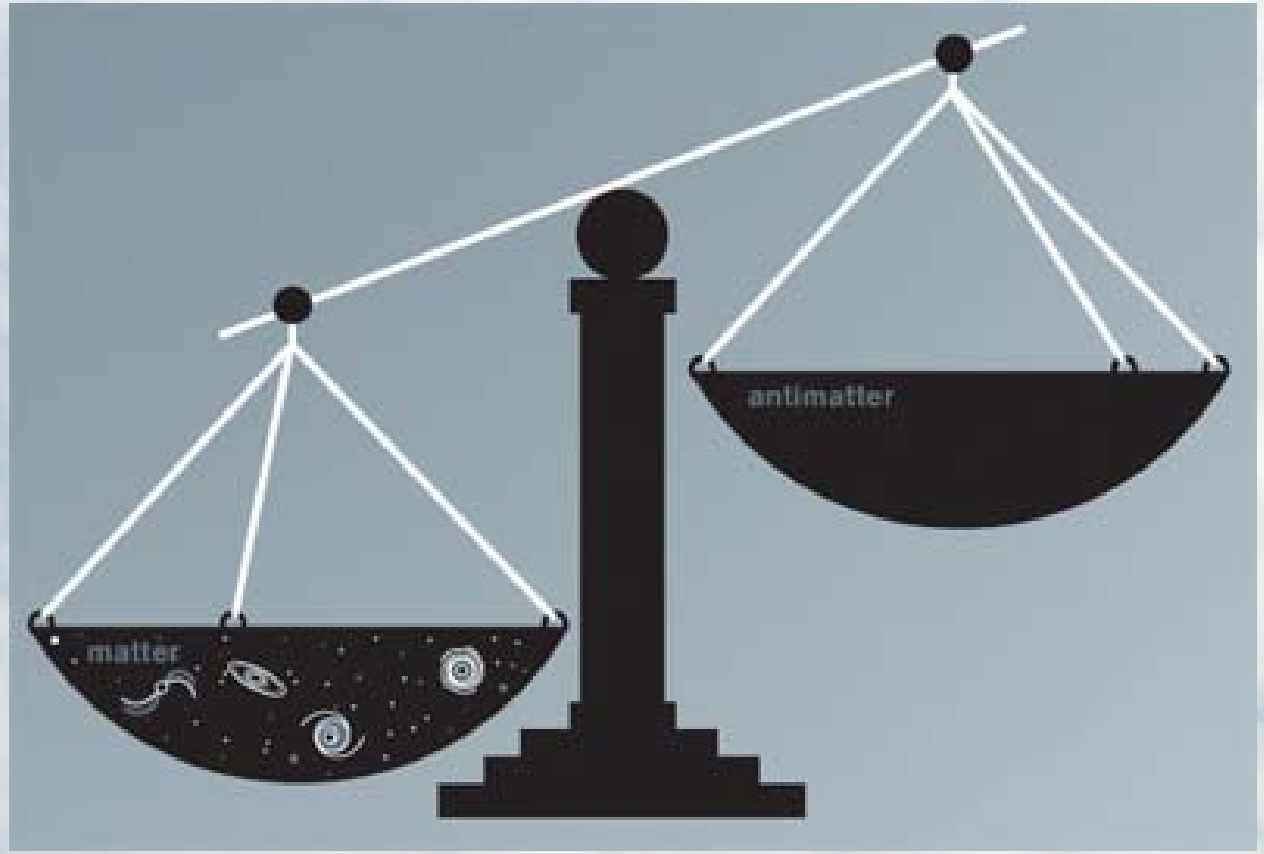
Seeking the Origin of Asymmetry

Xin Qian
BNL

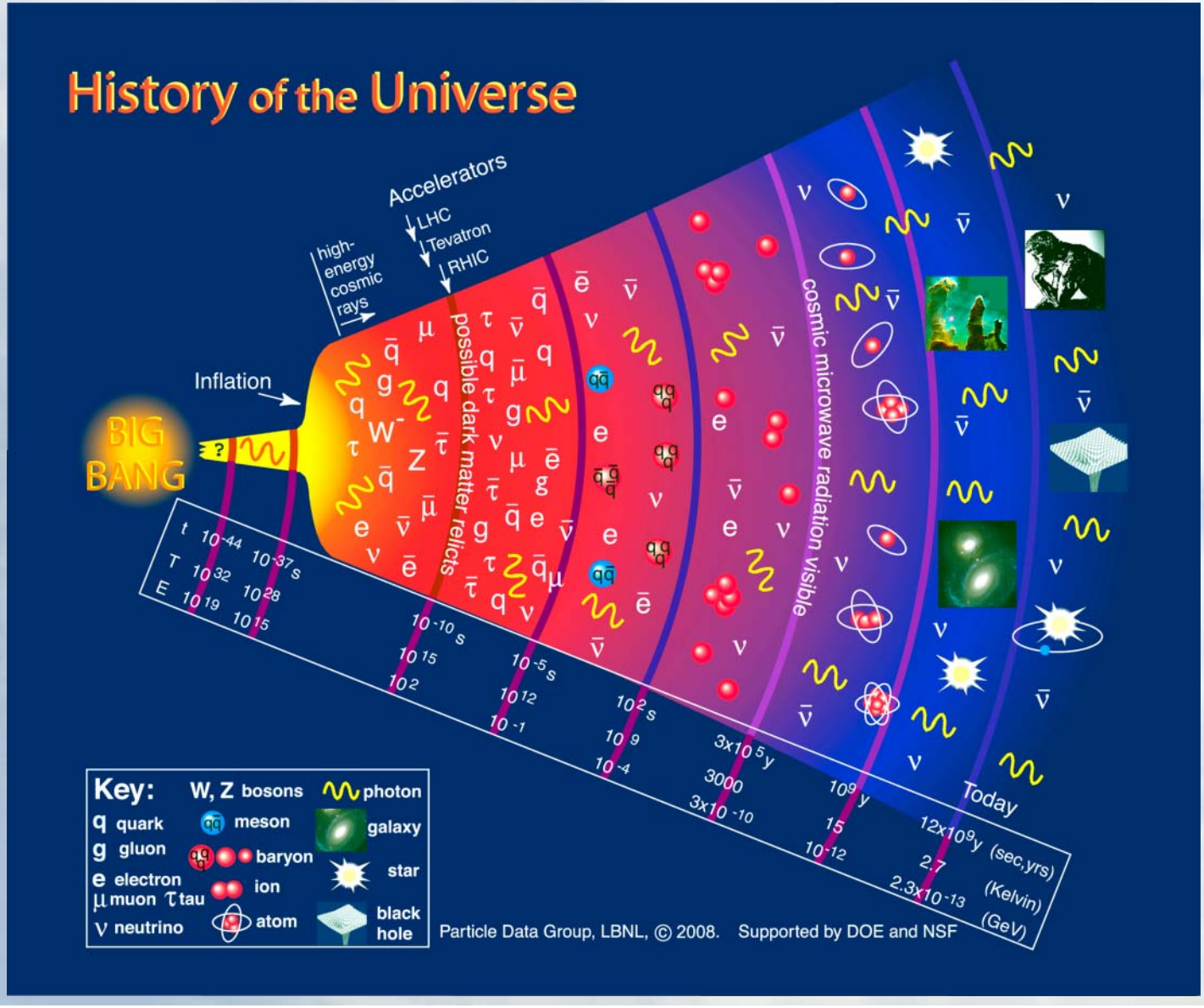


Outline

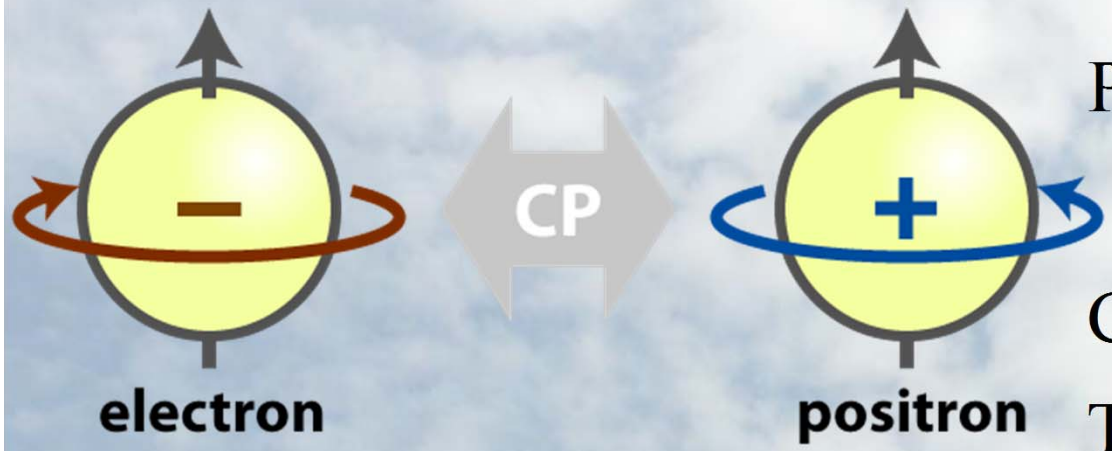
- The Big Question:
  - Why is there much more matter than anti-matter in our universe?
  - Is neutrino the key to this question?
- The Overall Strategy:
  - Neutrino vs. Antineutrino oscillations
  - Will there be a signal?
  - Will the detector technology be viable?
- The Experimental Design and Future Challenges

Where is all the anti-matter?

$$\eta := \frac{N_{baryon}}{N_{\gamma}} = \begin{cases} (6.0 \pm 0.1) \times 10^{-10} & \text{(BBN)} \\ (6.0 \pm 0.07) \times 10^{-10} & \text{(CMB)} \end{cases}$$



CP Violation: Asymmetry between Matter and Anti-matter



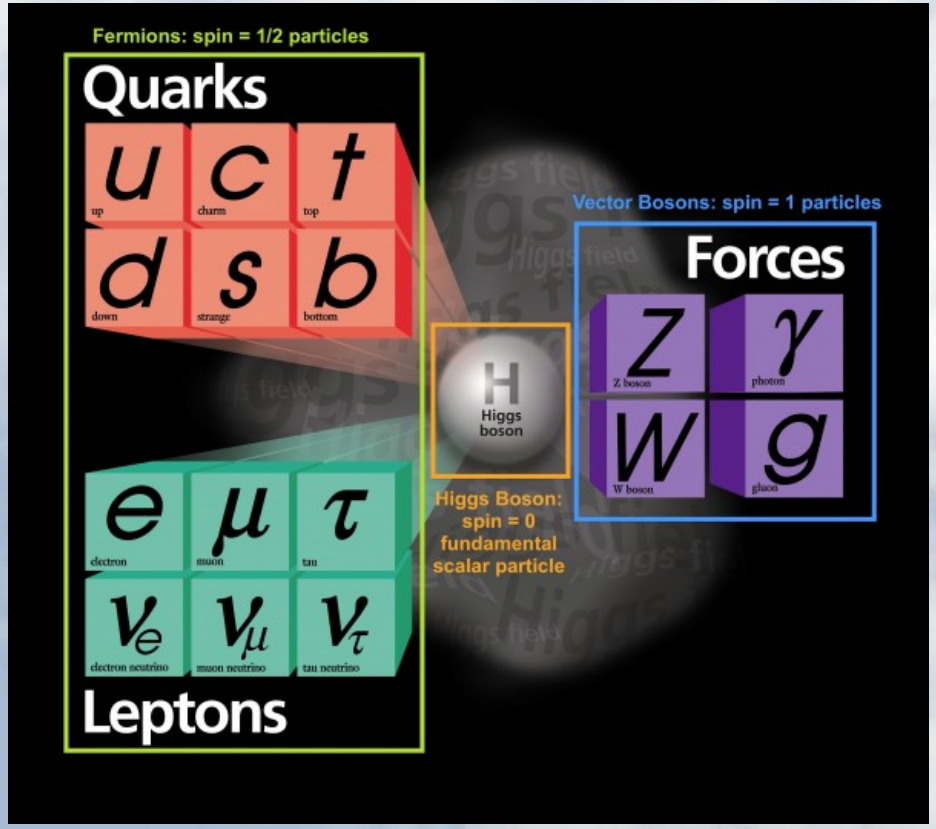
Parity (P): $\begin{pmatrix} x \\ y \\ z \end{pmatrix} \rightarrow \begin{pmatrix} -x \\ -y \\ -z \end{pmatrix}$

Charge (C): $q \rightarrow -q$

Time (T): $t \rightarrow -t$

CP violation → physics laws governing the interaction of matter are different from those governing anti-matter

Is there CP violation (CPV) in the Standard Model of Particle Physics?



Interaction	Mediators	Relative Strength	Range (m)
Strong	**g**	**10^{38}**	**10^{-15}**
E&M	**γ**	**10^{36}**	**∞**
Weak	**W, Z**	**10^{25}**	**10^{-18}**
Gravitation	gravitons	1	∞

$$\eta := \frac{N_{baryon}}{N_\gamma} = \begin{cases} (6.0 \pm 0.1) \times 10^{-10} & \text{(BBN)} \\ (6.0 \pm 0.07) \times 10^{-10} & \text{(CMB)} \end{cases}$$

- Yes, CPV exists in the quark sector, but not enough to explain the observed asymmetry
- What about the lepton (neutrino) sector?

Outline

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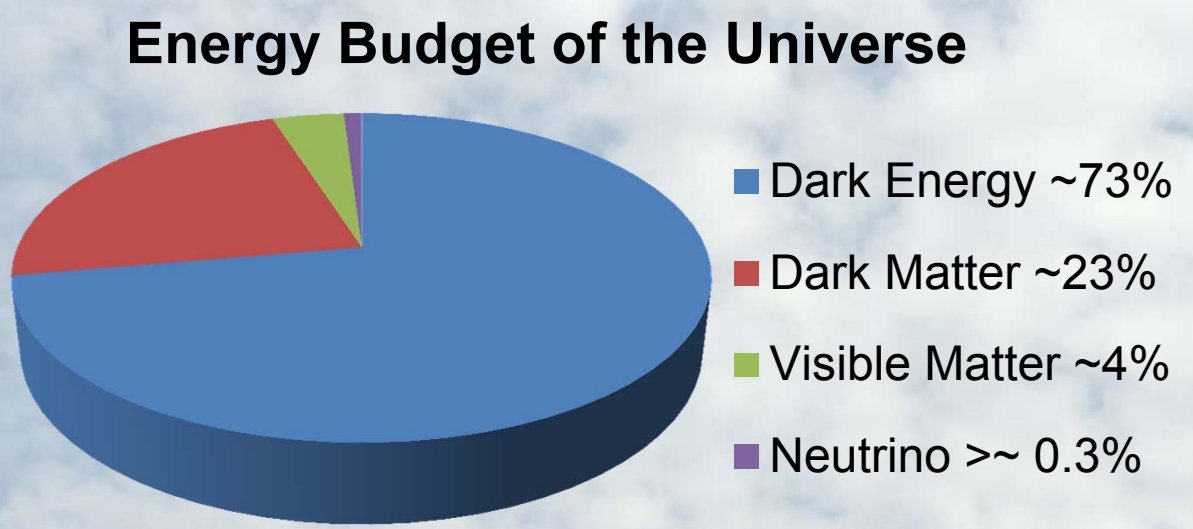
  - Will the detector technology be viable?

- The Experimental Design and Future Challenges

Some Facts about the Neutrino

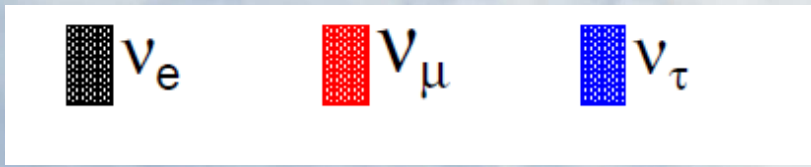
- Neutrinos interact through weak interaction
  - **It takes a wall thicker than our galaxy to stop a neutrino**
- Neutrinos have non-zero mass
  - **Physics beyond the standard model**

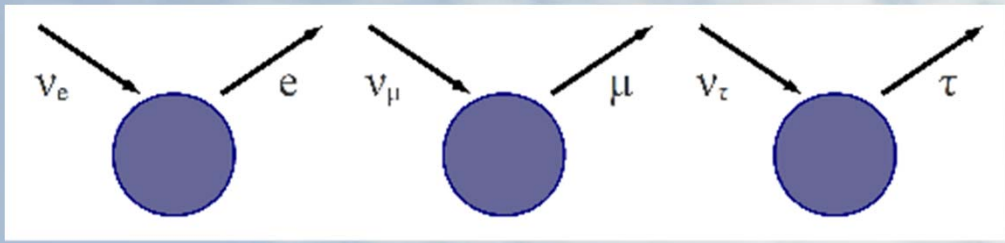


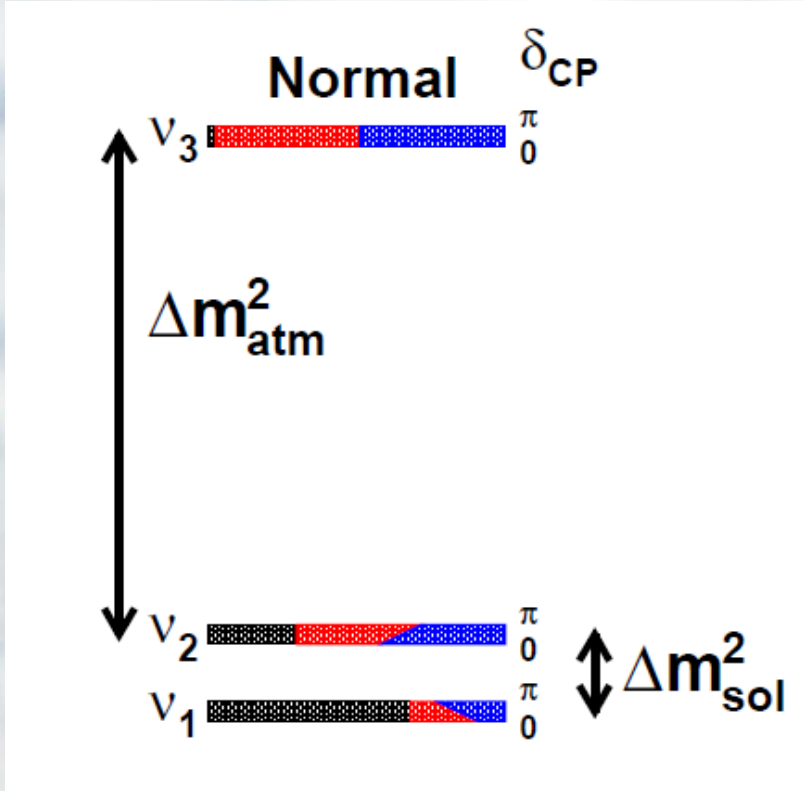
- The smallness of neutrino mass also suggests a new mechanism of the mass generation

Some Facts about the Neutrino

- Neutrino Flavor Eigenstate $\neq$ Mass Eigenstate







Neutrino Oscillation

Neutrino Flavor Eigenstate $\neq$ Neutrino Mass Eigenstate

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \quad \begin{matrix} m_1 \\ m_2 \end{matrix}$$

Neutrino are produced and detected by weak interaction, but propagate as mass eigenstates.

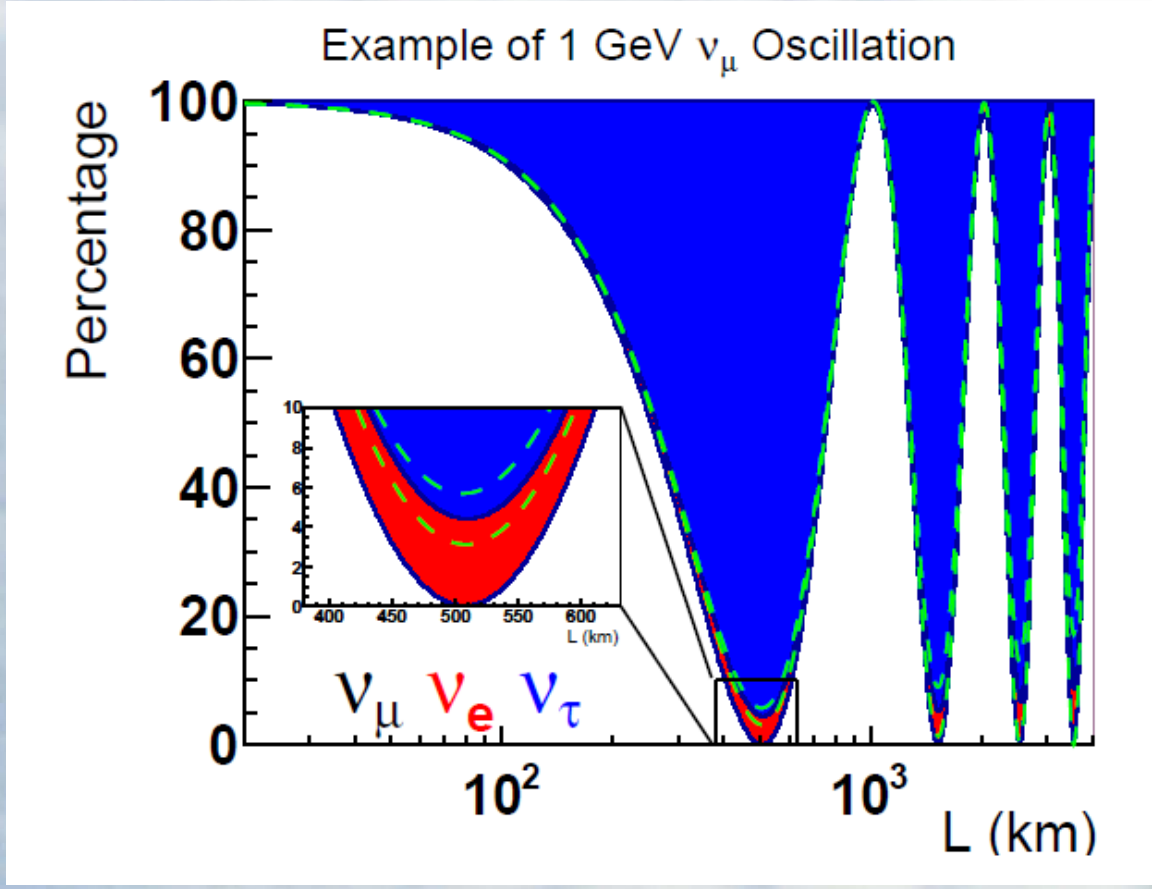
$$|\nu_\alpha(t)\rangle = \cos\theta \cdot e^{-i(P_1 \cdot r - Et)} |\nu_1(0)\rangle + \sin\theta \cdot e^{-i(P_2 \cdot r - Et)} |\nu_2(0)\rangle$$

Appearance $\quad P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(1.27 \Delta m_{21}^2 \left[eV^2\right] \frac{L\left[km\right]}{E\left[GeV\right]}\right)$

Survival $\quad P(\nu_\alpha \to \nu_\alpha) = 1 - P(\nu_\alpha \to \nu_\beta) \quad \left(\Delta m_{ij}^2 = m_i^2 - m_j^2\right)$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

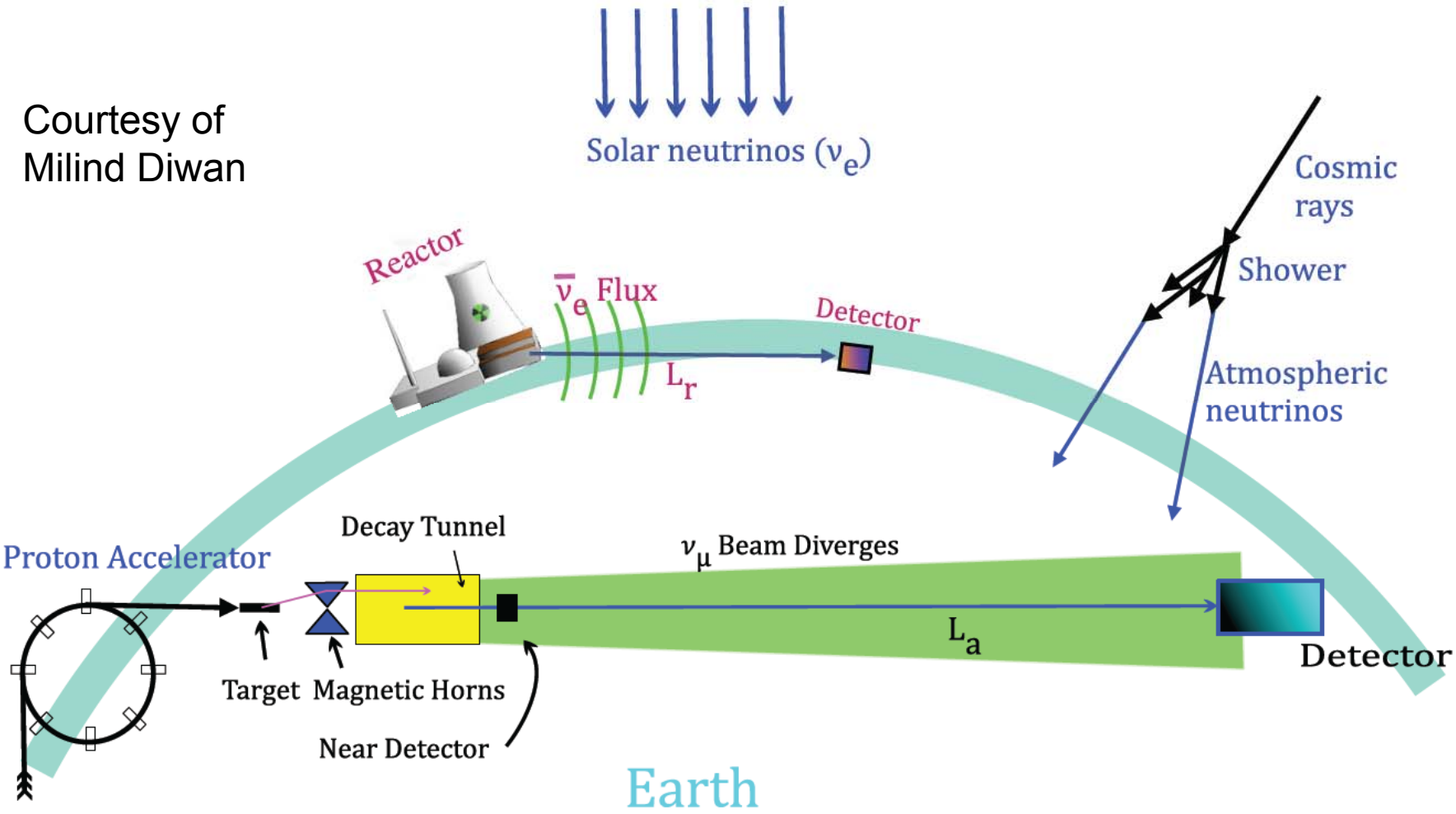
$\theta_{23} \sim 45^\circ$ **θ_{13} and δ_{CP}** $\theta_{12} = \sim 32^\circ$



CP-violation: $P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$

Available Neutrino Sources

Courtesy of
Milind Diwan



CP-violation: $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$

Periodic Summary

- To find the origin of matter-anti-matter asymmetry, we decide to look at the neutrino sector

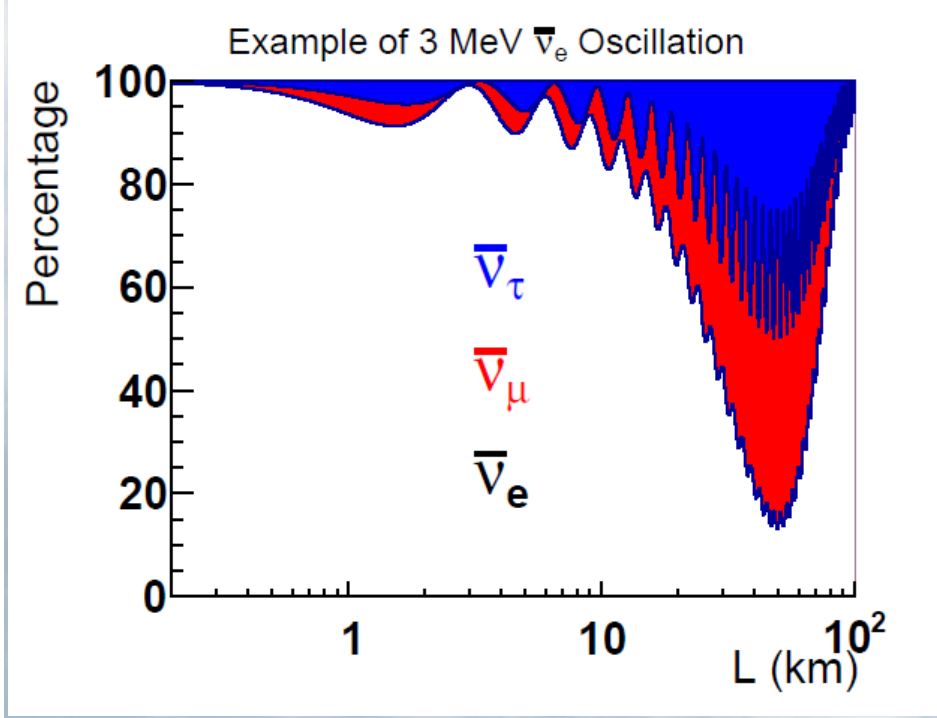
- With all available channels and practical constraints, we decide to search for new CP violation

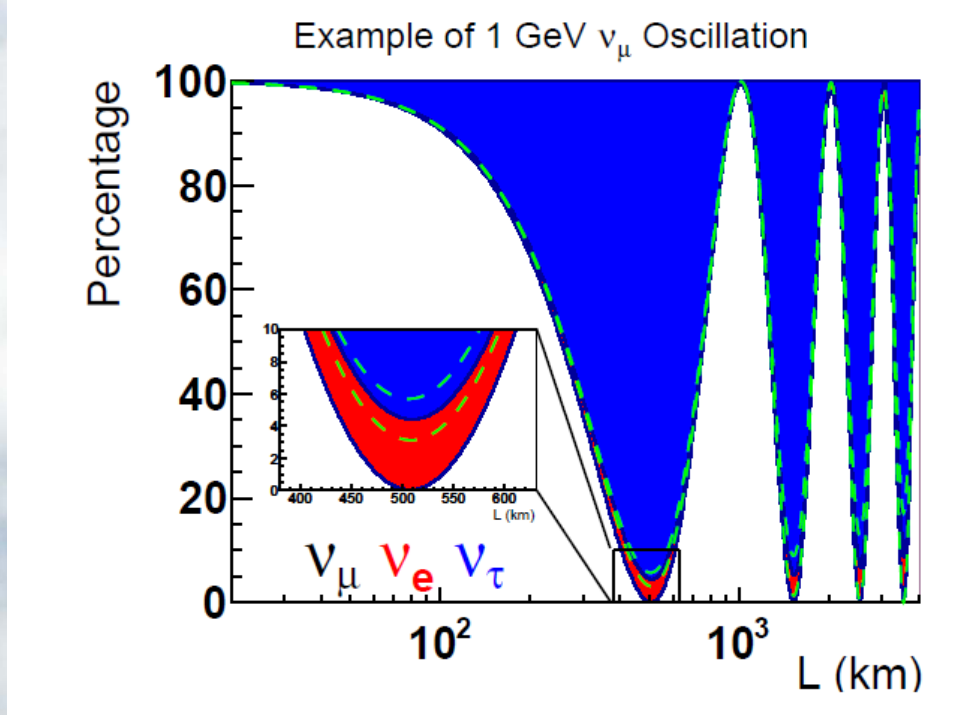
$$\text{CP-violation:} \quad \mathrm{P}\left(\nu_\mu \to \nu_e\right) \neq \mathrm{P}\left(\bar{\nu}_\mu \to \bar{\nu}_e\right)$$

- Is this approach viable?

- What about the detector technology?

Will the signal be non-zero? θ_{13}





$$P\left(\bar{\nu}_e \to \bar{\nu}_e\right) \propto 1 - \sin^2 2\theta_{13}$$

$$P(\nu_\mu \to \nu_e) \propto \sin^2 2\theta_{13}$$

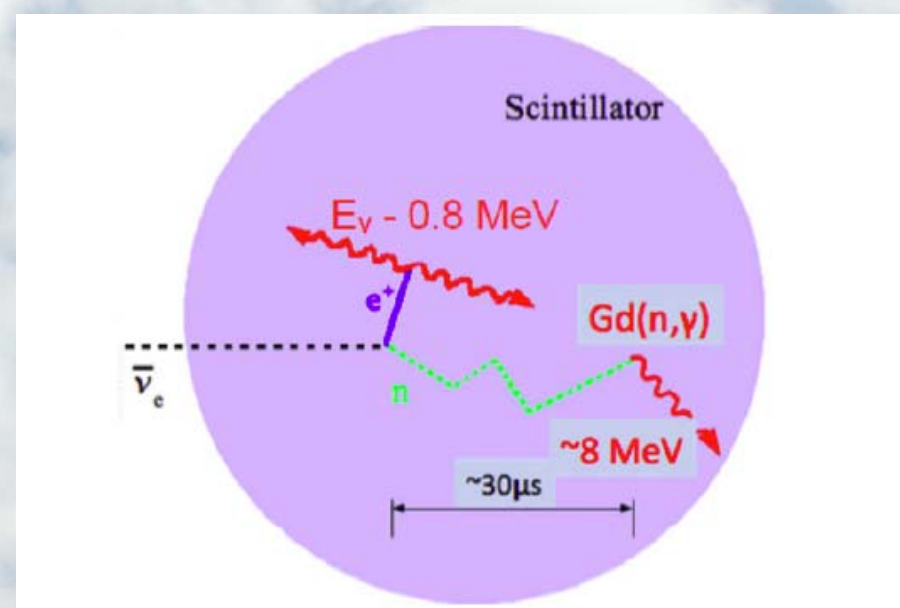
- Θ_{13} is one of three neutrino mixing angles
- Its value was unknown prior 2012
- Do a new experiment to measure Θ_{13} : Daya Bay

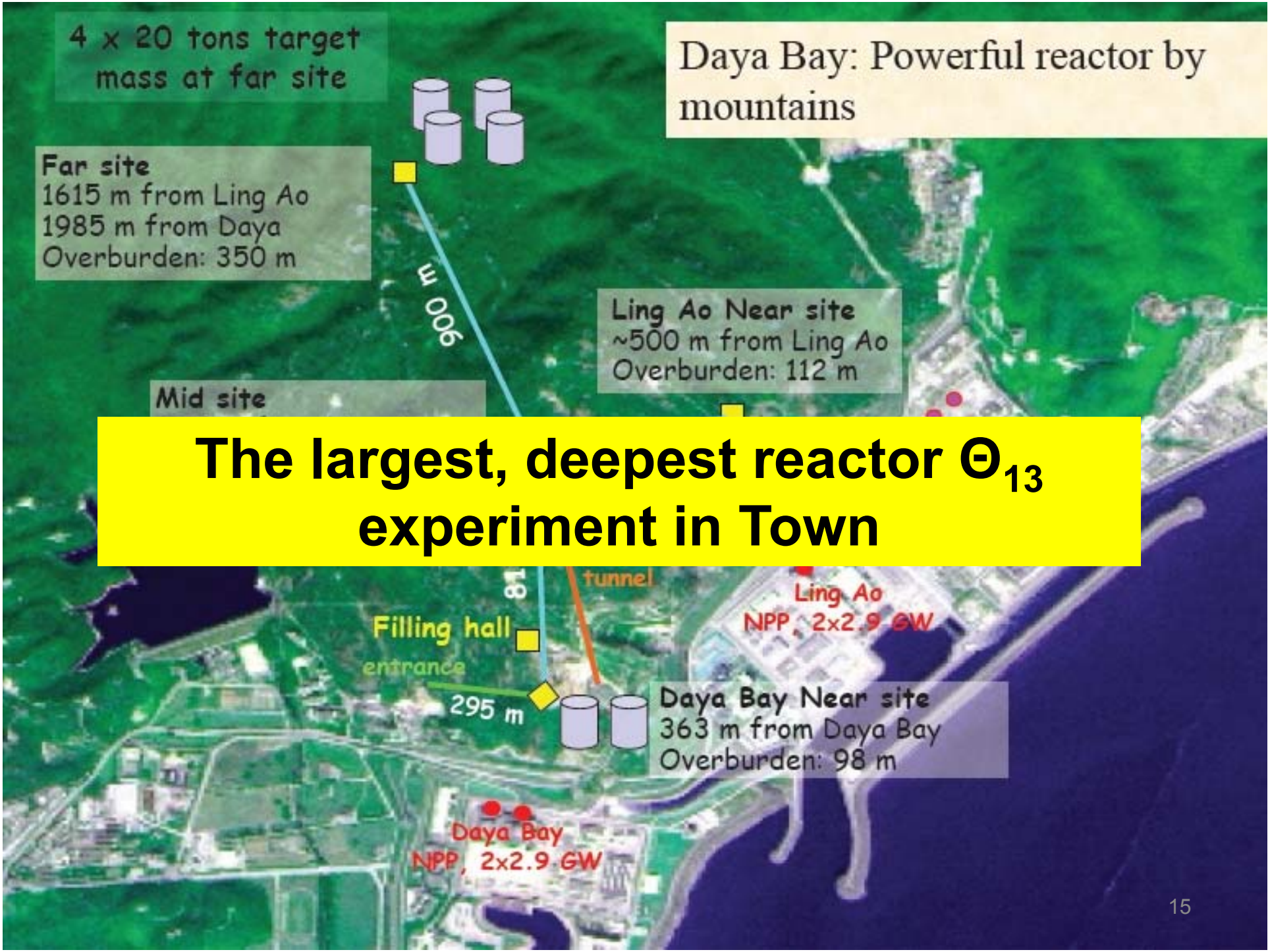
Reactor Neutrinos

- Pure anti-ν_e source
- ~ 6 anti-ν_e per fission
- ~ 2 x 10^{20} anti-ν_e/GW_{th}/sec
- At 1 km, ~1 event /day/ton/GW

Inverse Beta Decay

$$\overline{\nu}_e + p \rightarrow e^+ + n$$




4 x 20 tons target mass at far site
Daya Bay: Powerful reactor by mountains
Far site
1615 m from Ling Ao
1985 m from Daya
Overburden: 350 m
900 m
Ling Ao Near site
~500 m from Ling Ao
Overburden: 112 m
Mid site
The largest, deepest reactor Θ13 experiment in Town
810
tunnel
Ling Ao
NPP, 2x2.9 GW
Filling hall
entrance
295 m
Daya Bay Near site
363 m from Daya Bay
Overburden: 98 m
Daya Bay
NPP, 2x2.9 GW

Keys to High Precision

- Statistics → Precision
  Powerful reactors (17.6 GW) + Large Mass (80 ton)

Far/Near ν_e Ratio

Distances from reactor

Oscillation deficit

$$\frac{N_{far}}{N_{near}} = \left(\frac{L_n}{L_f}\right)^2 \cdot \left(\frac{P_{survival}(E, L_f)}{P_{survival}(E, L_n)}\right)$$

- Systematics → Accuracy
  - Reactor: using near/far to form ratio + baseline (near ~0.4 km, far ~1.7 km)
  - Detector: “identical detectors” + “precise detector calibration”
  - Background: deep underground + active/passive shielding

Daya Bay Anti-ν_e Detector

Automated calibration system

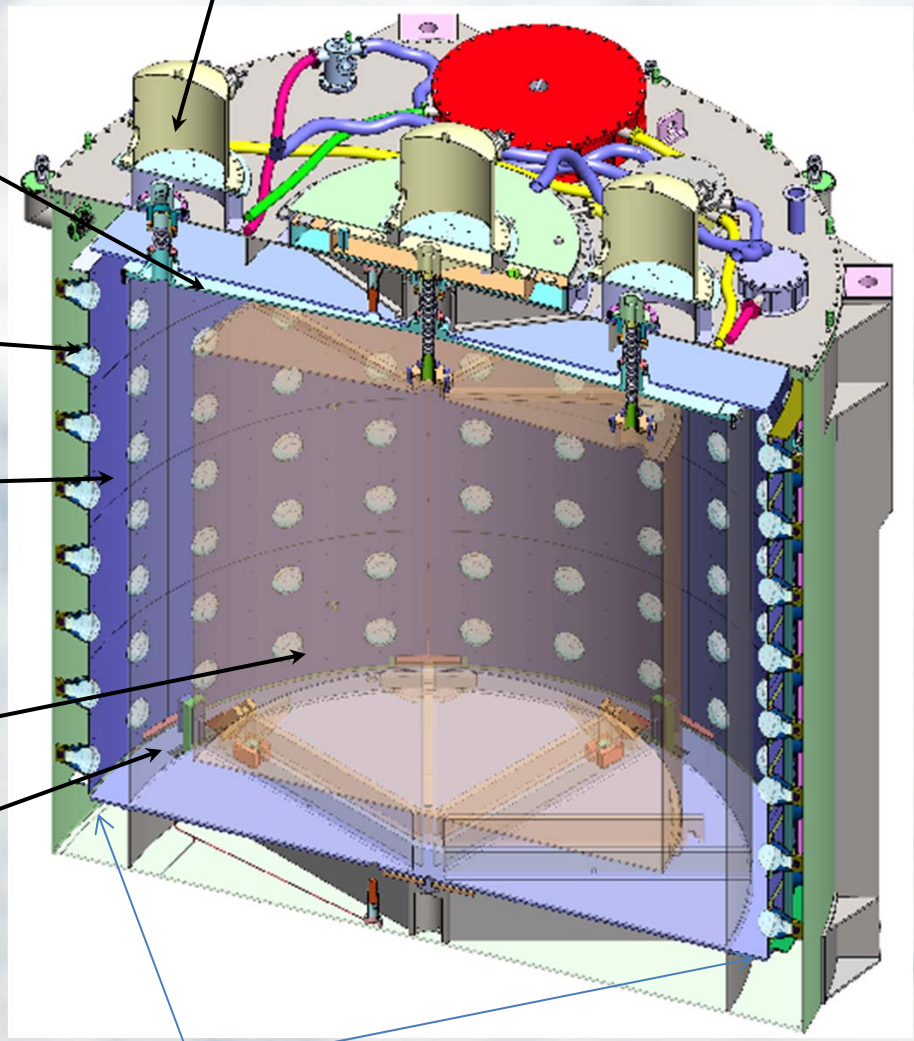
Reflectors at top/bottom of cylinder

192 Photomultipliers on the outside wall

Steel tank
40 ton mineral oil

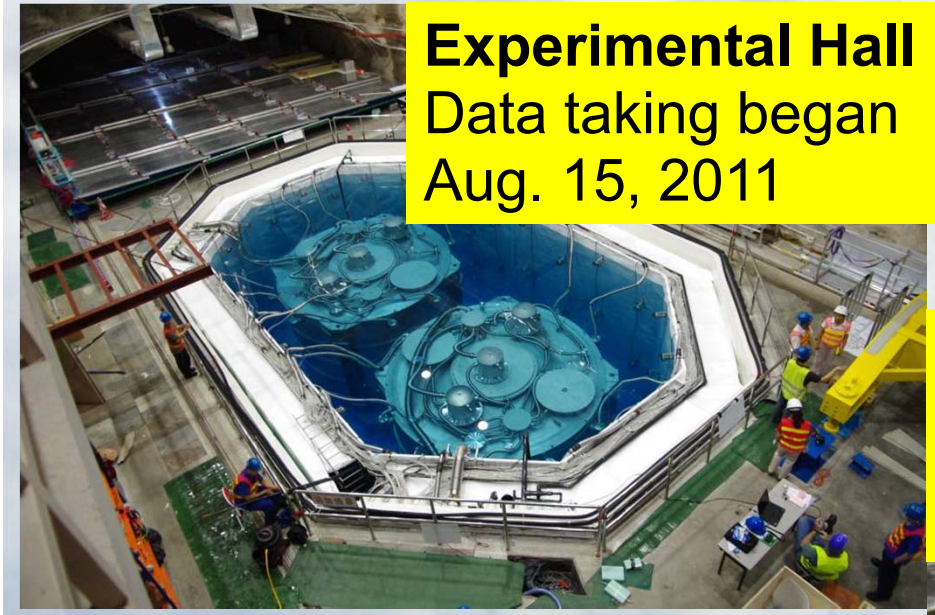
Inner acrylic tank
20 ton Gd-loaded liquid scintillator

Outer acrylic tank
20 ton liquid scintillator



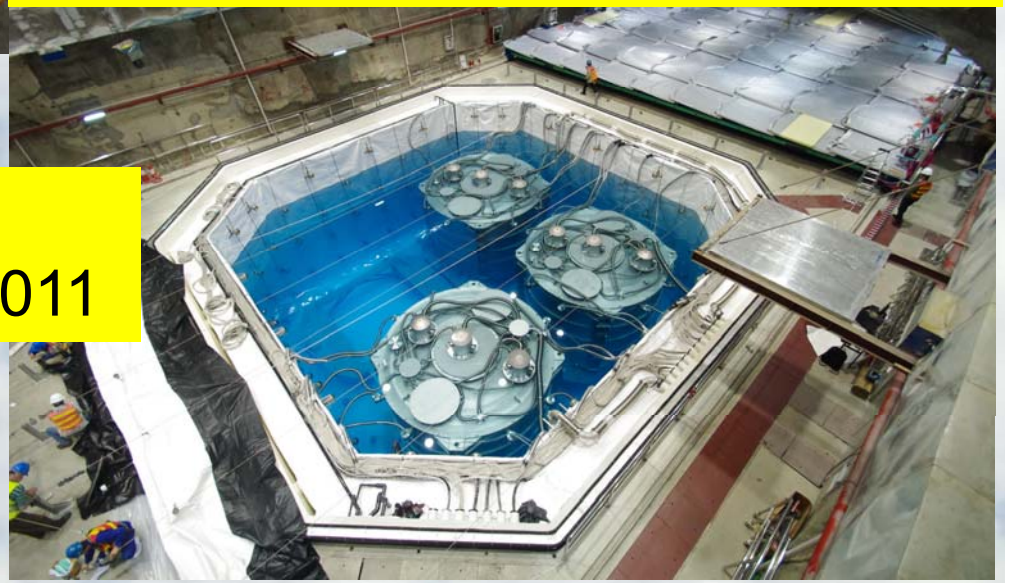
5 m diameter

Detectors in 3 Sites

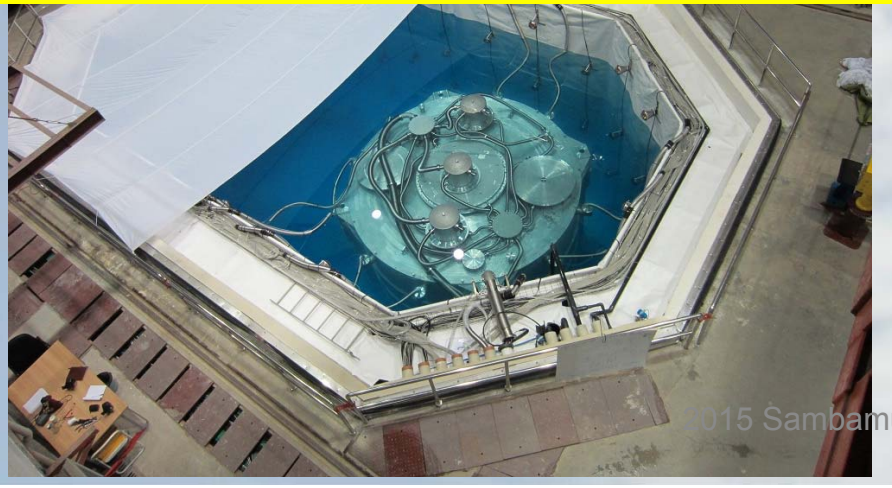


Experimental Hall 1
Data taking began
Aug. 15, 2011

Experimental Hall 3: Began 3 detectors operation on
Dec. 24, 2011



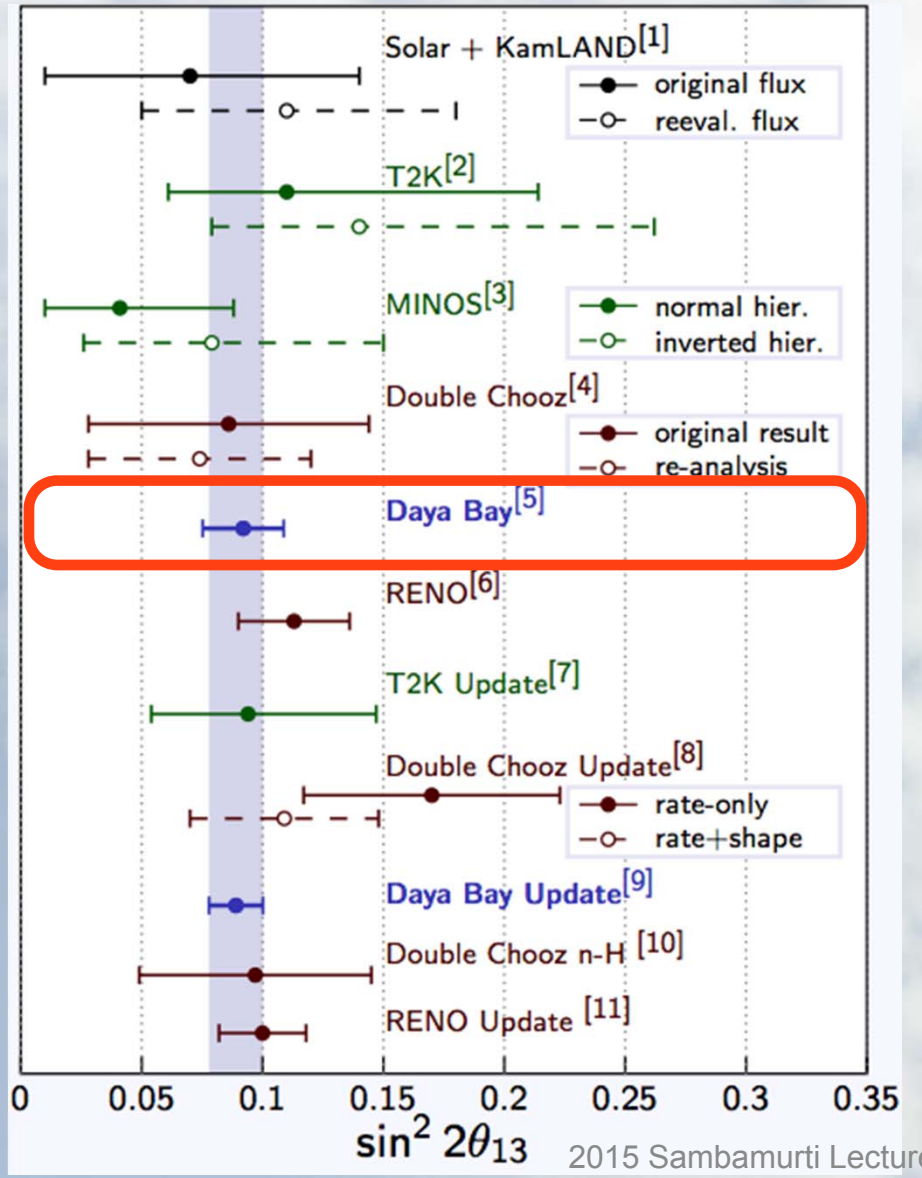
Experimental Hall 2: Began 1 detector operation on Nov. 5, 2011

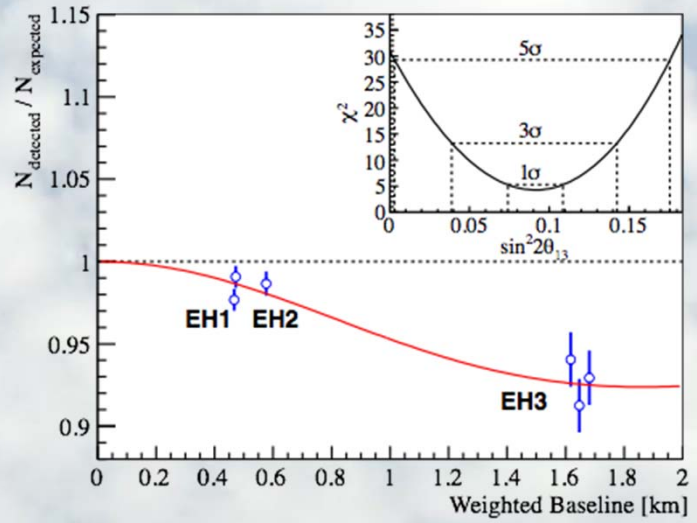


The Hunting Race for θ_{13} Since 2011

2011

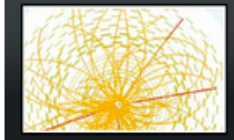
2013





March 2012, Daya Bay reported the discovery of non-zero value of θ_{13} with a statistical significance > 5σ

A Top-10 Scientific Breakthrough of 2012



FREE ACCESS

The Discovery of the Higgs Boson

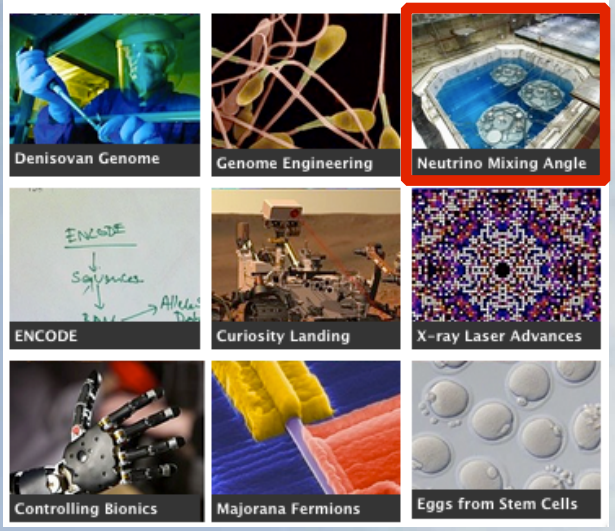
A. Cho

Exotic particles made headlines again and again in 2012, making it no surprise that the breakthrough of the year is a big physics finding: confirmation of the existence of the Higgs boson. Hypothesized more than 40 years ago, the elusive particle completes the standard model of physics, and is arguably the key to the explanation of how other fundamental particles obtain mass. The only mystery that remains is whether its discovery marks a new dawn for particle physics or the final stretch of a field that has run its course.

Read more about the Higgs boson from the research teams at CERN.

Runners-Up FREE WITH REGISTRATION

This year's runners-up for Breakthrough of the Year underscore feats in engineering, genetics, and other fields that promise to change the course of science.



TALENs, and another genome-editing tool called meganucleases is that they must be reengineered for each new DNA target. These proteins have two parts: the DNA targeting section and the DNA-cutting section. The new technology substitutes RNA—which is simpler to make than a piece of a protein—for the DNA targeting section. It also makes use of a bacterial protein called Cas9, which is part of a natural bacterial defense system called CRISPR, to do the cutting.

Researchers have shown in a test-tube that they can combine these two RNAs into a single one that both matches the DNA target and holds Cas9 in place. Using this system, they were able to cut specific target DNA, demonstrating the potential of Cas9 to work like TALENs. Now, those researchers are trying this approach in organisms other than bacteria, and other genome engineers are quite excited about their prospects, suggesting that it may one day challenge zinc finger nucleases and TALENs as the core genome engineering technology.

CRASH PROJECT OPENS A DOOR IN NEUTRINO PHYSICS

Sometimes it's not the result itself so much as the promise it holds that matters most. This year, physicists measured the last parameter describing how elusive particles called neutrinos morph into one another as they zip along at near-light speed. And the result suggests that in the coming decades neutrino physics will be every bit as rich as physicists had hoped—and may even help explain how the universe evolved to contain so much matter and so little antimatter.

RUNNER-UP

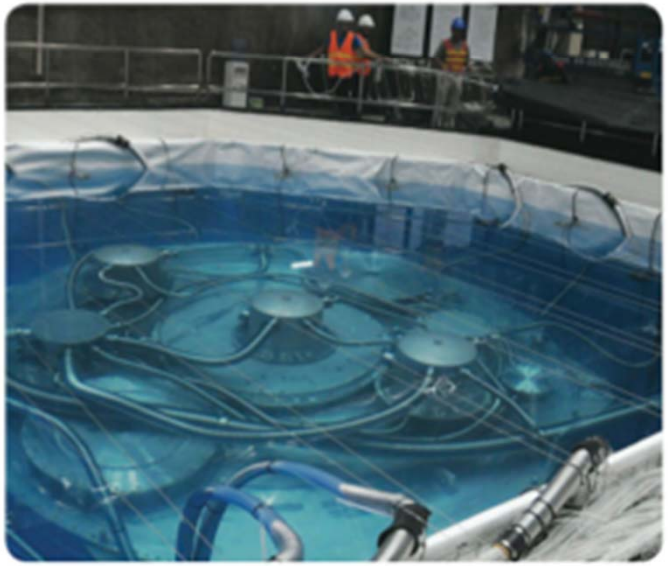
Born in certain nuclear interactions, neutrinos come in three types or flavors that change into one another in so-called neutrino oscillations. The rates and extents to which the flavors mix depend on six parameters: the three differences between the neutrinos' masses, and three "mixing angles." In March, the 250 researchers with the Daya Bay Reactor Neutrino Experiment in China reported that last unknown parameter, the mixing angle known as θ_{13} (pronounced "theta one three"), equals 8.8°, give or take 0.8°.

The result itself is remarkable, as it's not every year that physicists measure a new fundamental parameter. The real excitement, however, stems from the result's broader implications. The measurement proves that all three mixing angles are greater than zero. That fact, in turn, implies that the oscillations of antineutrinos might differ from those of neutrinos, something that would not be possible had θ_{13} equaled zero.

That's a big deal. Such a difference would analogous to the effect that created the matter-antimatter imbalance in the universe.

In fact, researchers in the United States, Japan, and Europe are engaged in experiments in which they use particle accelerators to fire neutrinos hundreds of kilometers through Earth to huge particle detectors. Current efforts seek to pin down, for example, the neutrinos emanating from the reactors at the Daya Bay Nuclear Power Plant and two neighboring plants in Shenzhen. In making a definitive measurement, they beat out teams working at reactors in France and South Korea and accelerator-based experiments in Japan and the United States.

The measurement of θ_{13} wasn't the only result in particle physics this year. Researchers working with the world's largest atom smasher, the Large Hadron Collider (LHC) in Switzerland, discovered the Higgs boson, the



That was fast! Construction of China's Daya Bay Reactor Neutrino Experiment began in 2007. With 2 months' worth of data, it scooped competitors in Japan, France, Korea, and the United States.

Science **338**, 1527

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$$\text{CP-violation:} \quad P\left(\nu_\mu \to \nu_e\right) \neq P\left(\bar{\nu}_\mu \to \bar{\nu}_e\right)$$

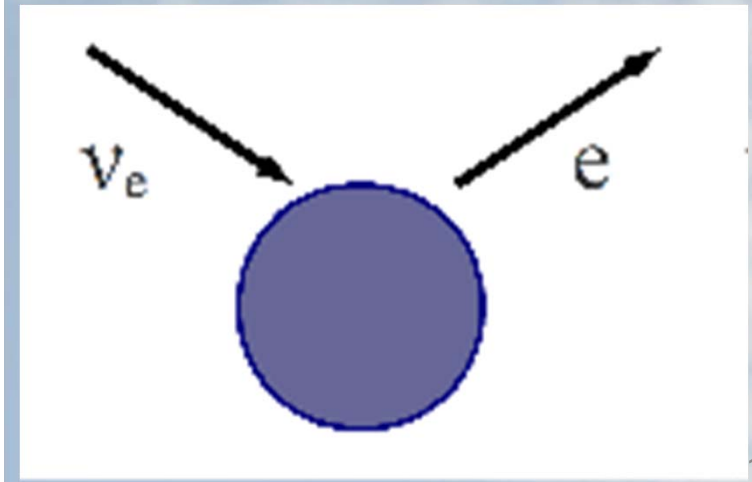
- Is this approach viable?

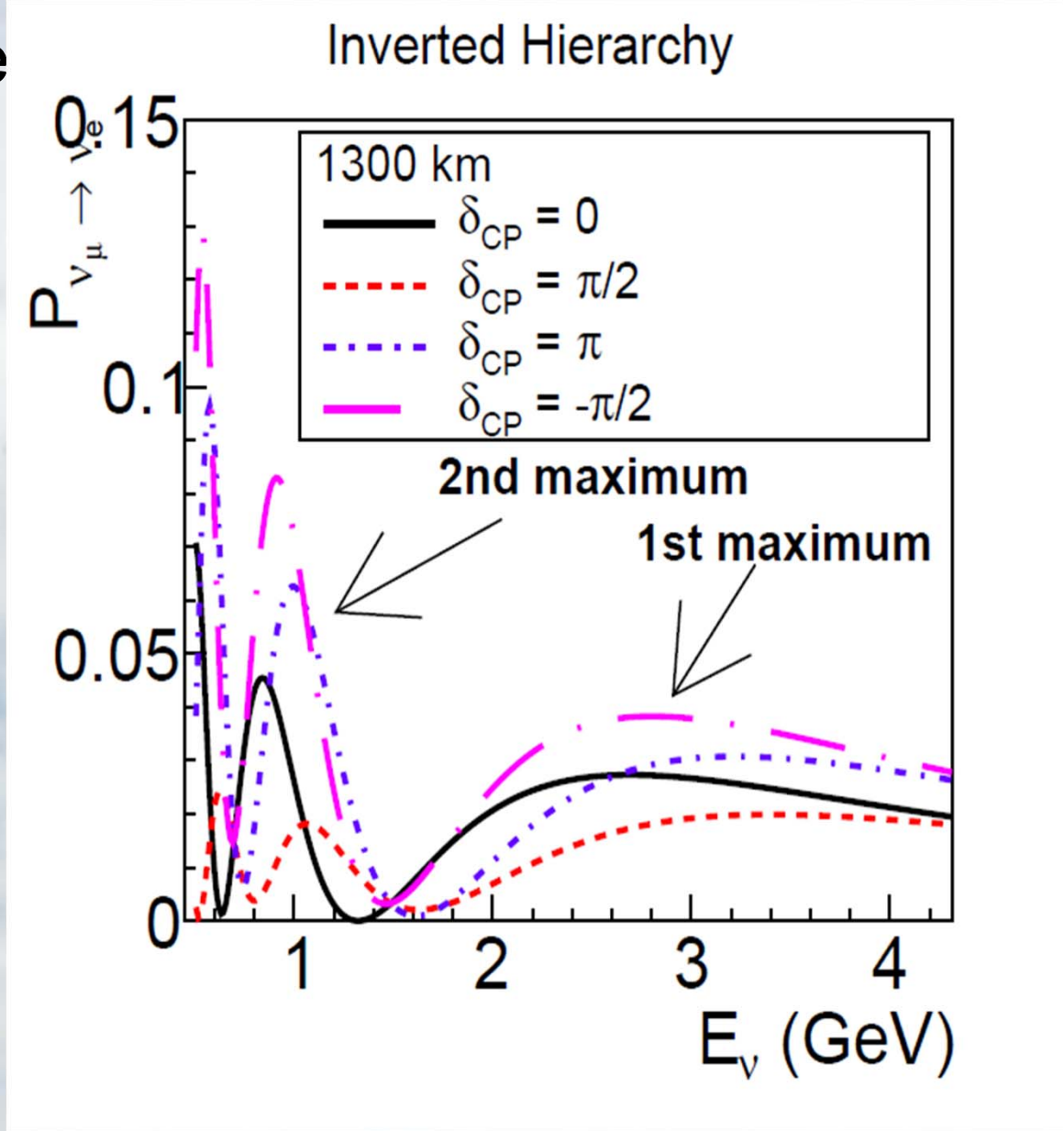
Yes, θ_{13} is non-zero ~ 8.4°

- What about the detector technology?

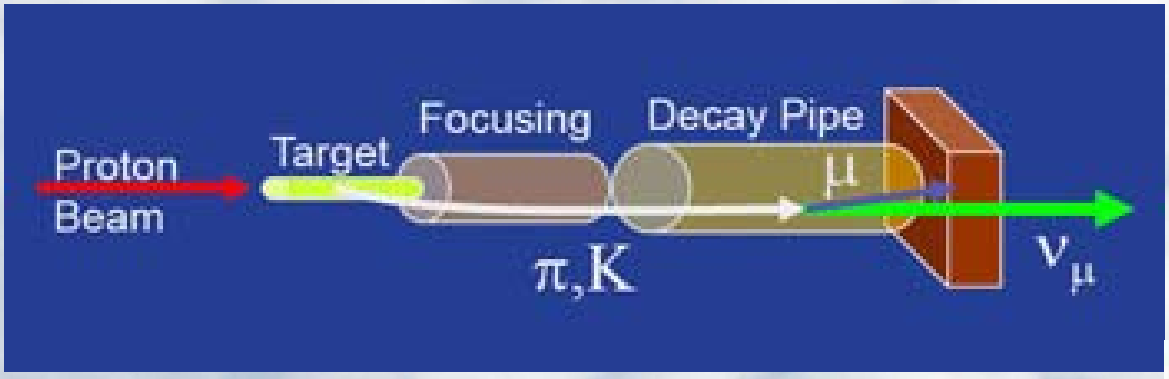
Signal: $\nu_\mu \rightarrow \nu_e$ Appearance

- Oscillation patterns are very sensitive to the δ_{CP} and the mass hierarchy



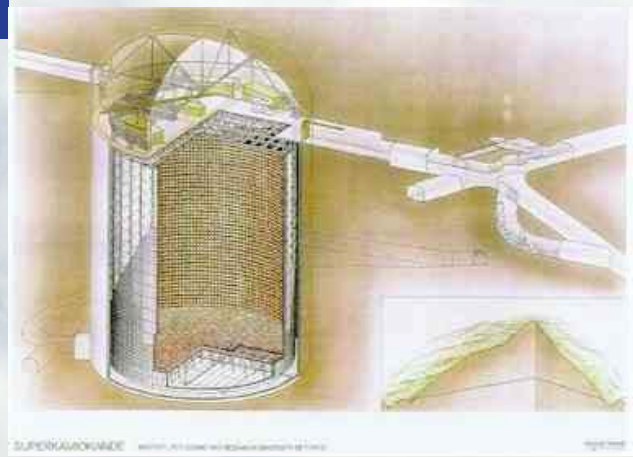


Accelerator Neutrino Experiment

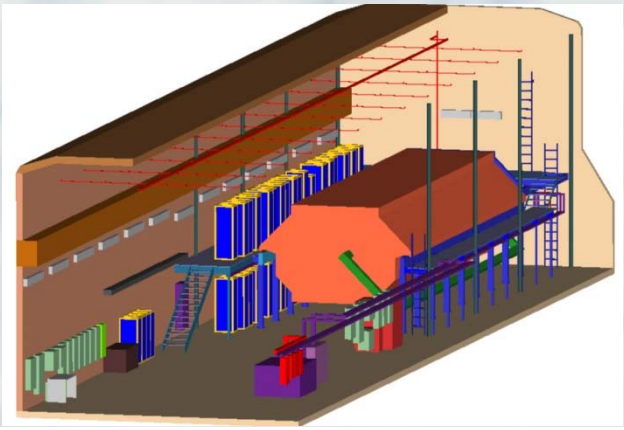


$$\pi^+ \rightarrow \mu^+ + \nu_\mu (\sim 100\%)$$

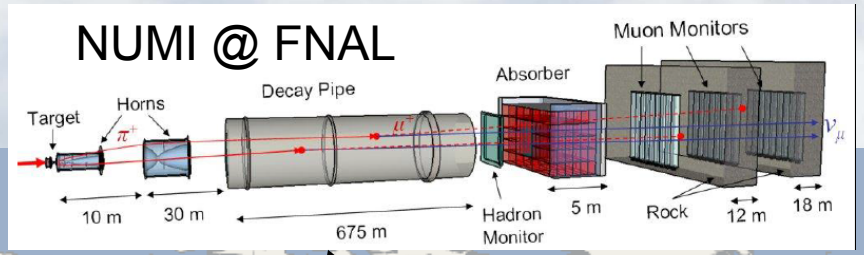
...

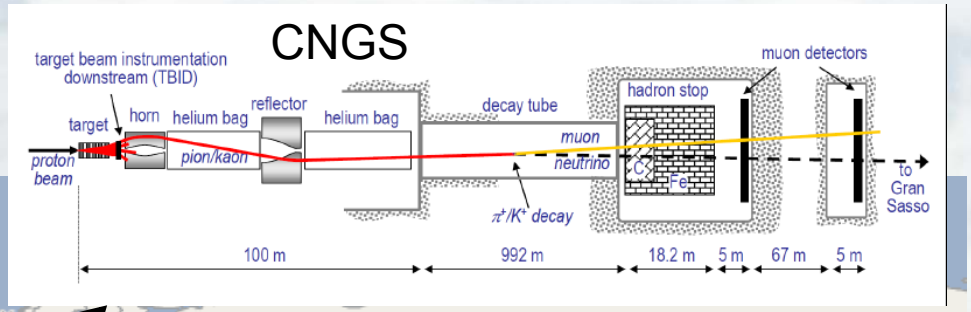


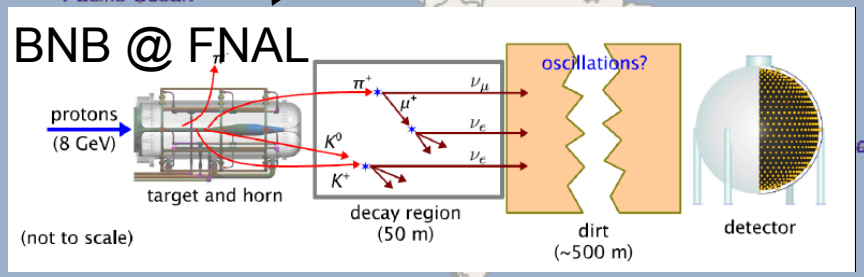
- Accelerator Neutrino Beam
- Far Detector to measure Neutrino Oscillation
- Near Detector to categorize Neutrino beam

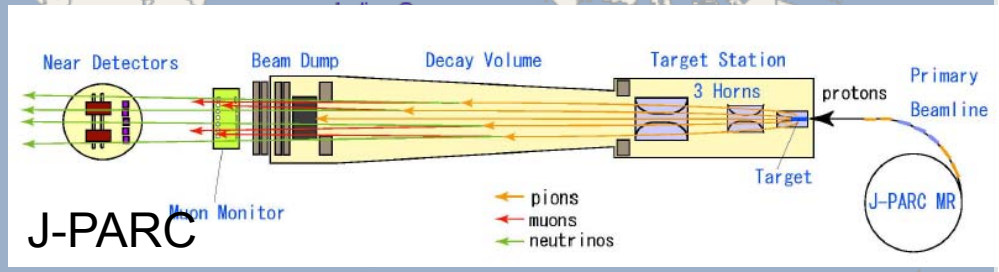


Recent Accelerator Neutrino Beams

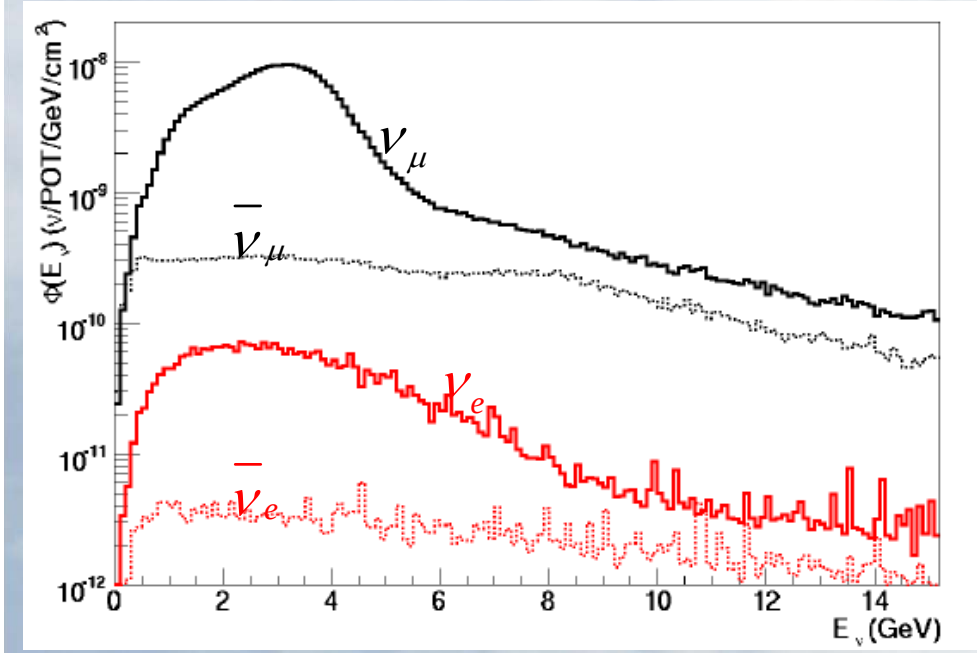








Signal and Background

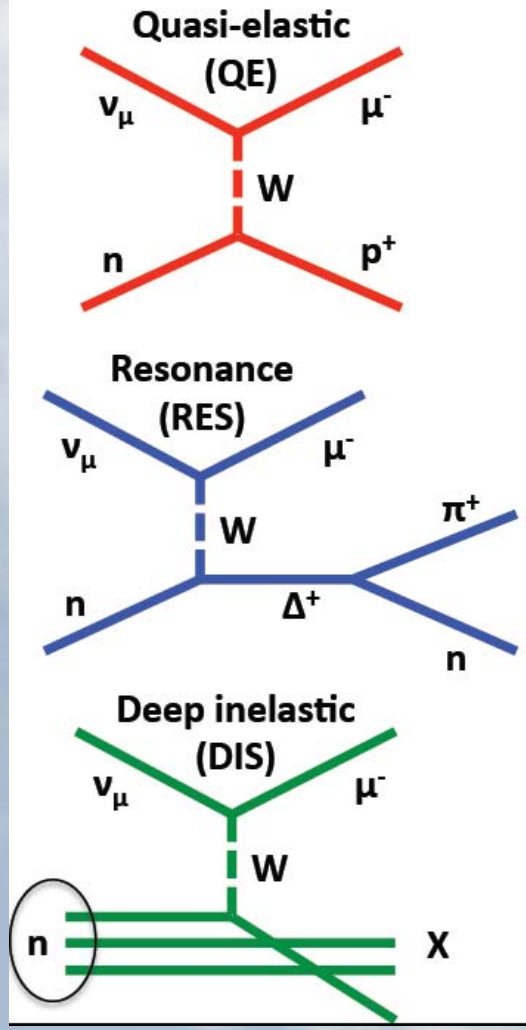


Charge-Current
$$\begin{cases} \nu_e + A \rightarrow e^- + X \\ \bar{\nu}_e + A \rightarrow e^+ + X \\ \nu_\mu + A \rightarrow \mu^- + X \\ \bar{\nu}_\mu + A \rightarrow \mu^+ + X \\ \nu_\tau + A \rightarrow \tau^- + X \\ \bar{\nu}_\tau + A \rightarrow \tau^+ + X \end{cases}$$

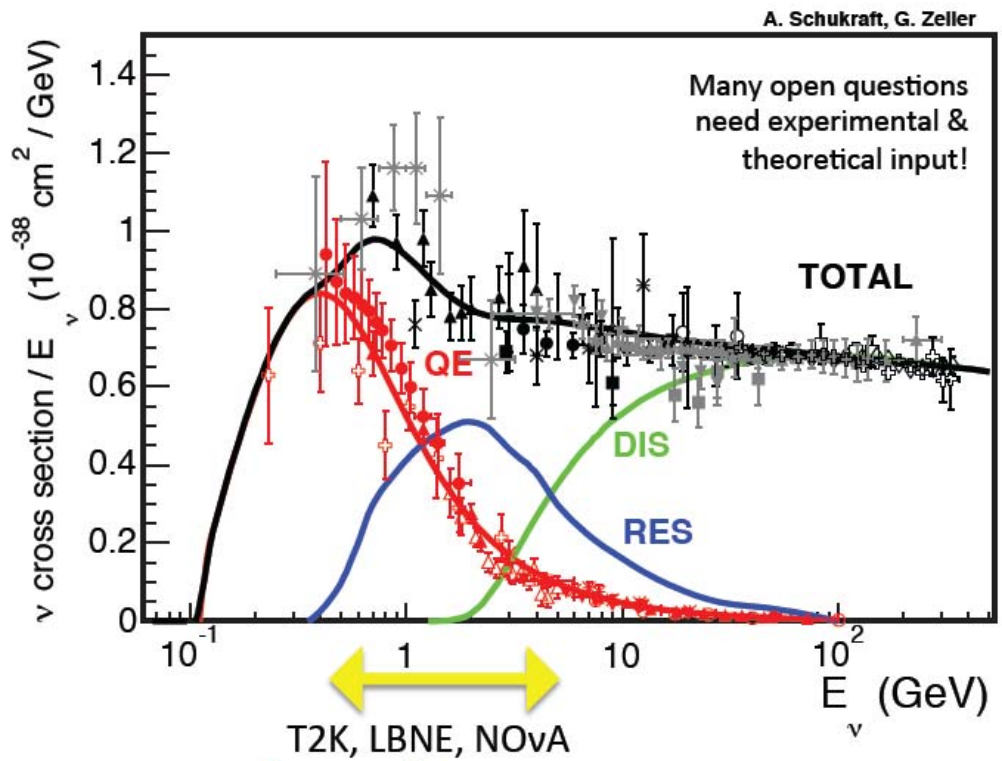
Neutral-Current: $\nu + A \rightarrow \nu + X$

It is important to have a detector which can pick up the electron-neutrinos

Neutrinos interacting with nucleons



Lots of interesting (nuclear) physics over all energy ranges.

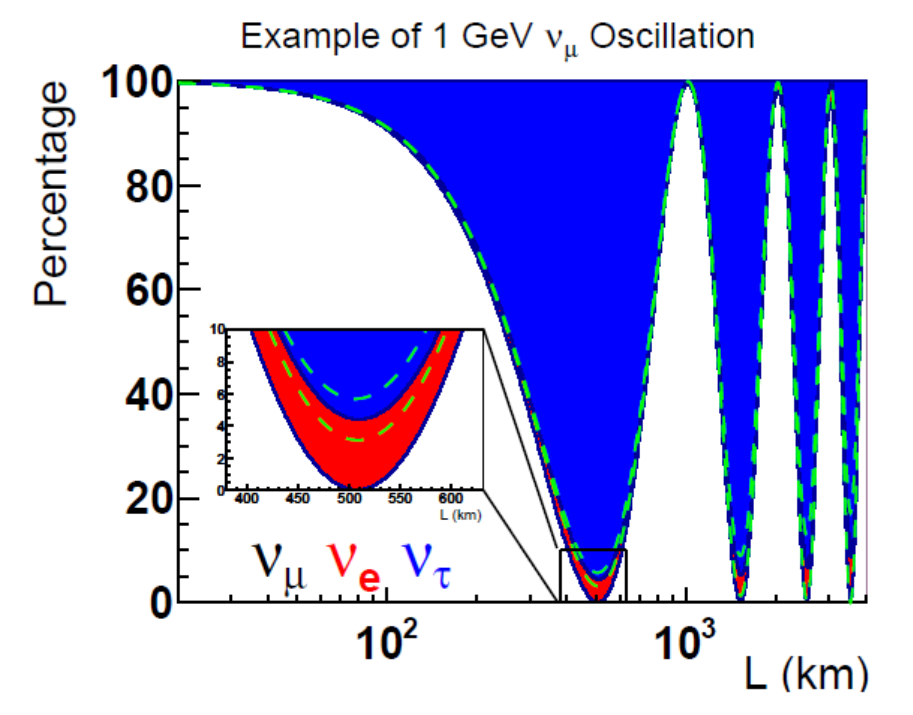


MicroBooNE: perfect to explore the QE regime!

It is important to have a detector which can differentiate these reactions

Requirements on Detector Technology

- Capability to have excellent differentiation power between signal and background for various reactions

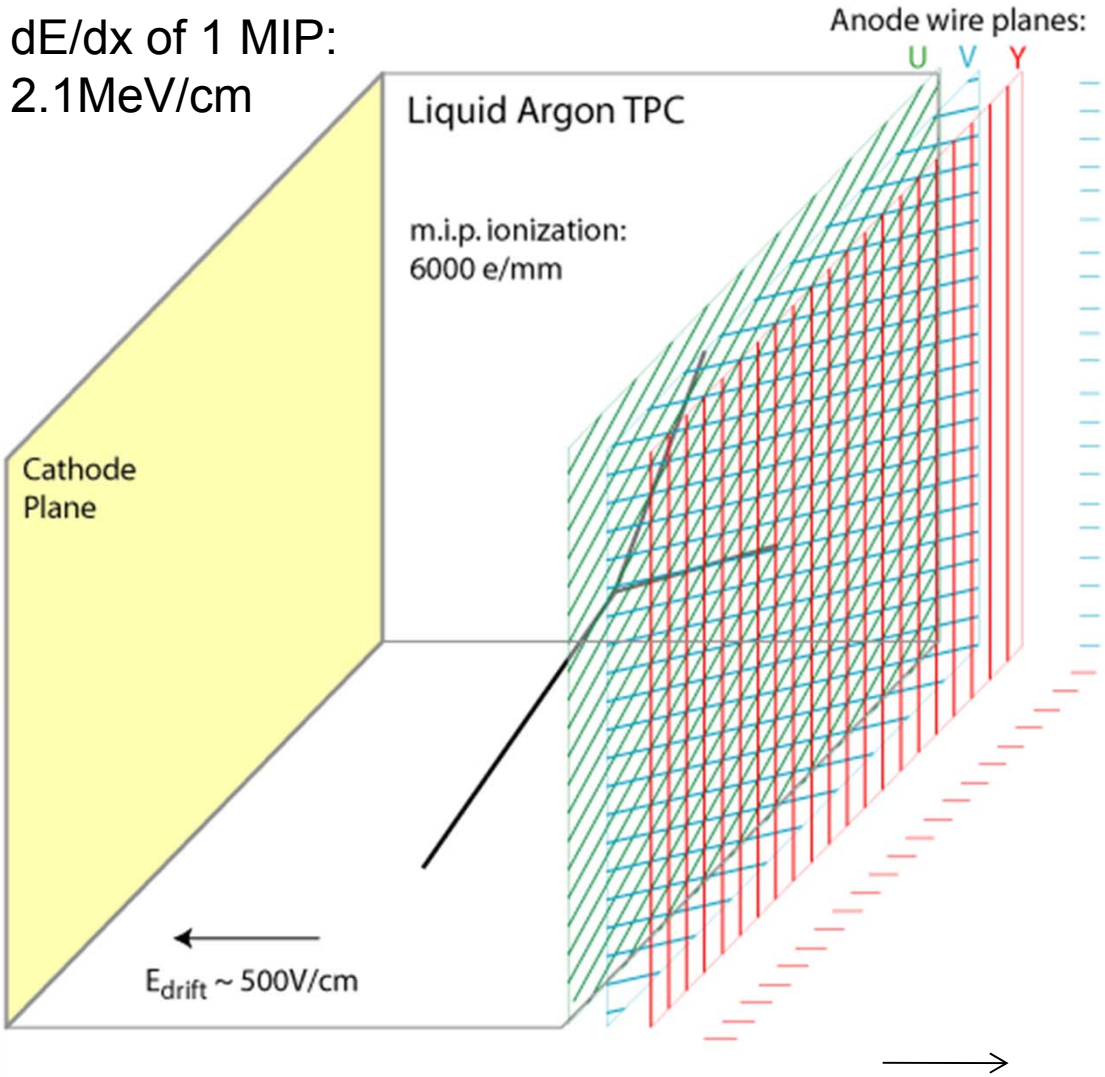


- Detector needs to be able to scale to several 10s of kton economically

Answer: Liquid Argon Time Projection Chambers
3D Image of Neutrino Interaction

Excellent new opportunity with high res. LArTPC

dE/dx of 1 MIP:
2.1MeV/cm

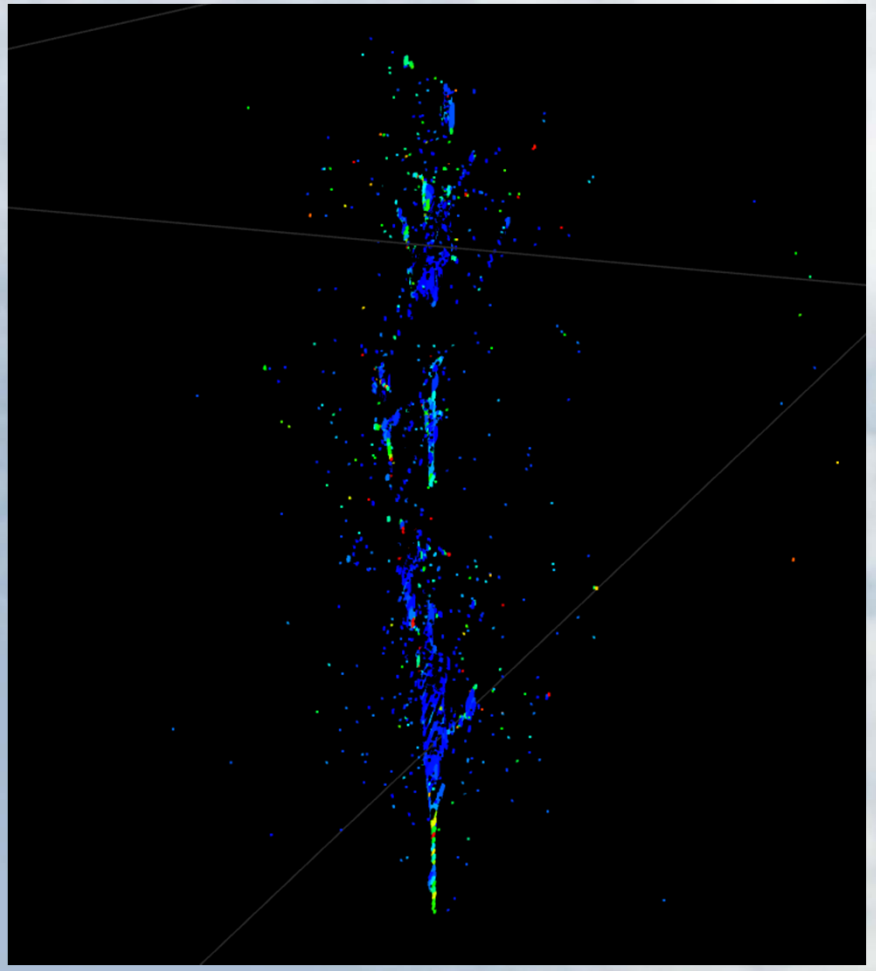


- Argon: most abundant noble gas (1.3% by weight)
- Electron drift v: 1.6 km/s
- Position resolution ~ mm
- PID: dE/dx through charge collection + event topology

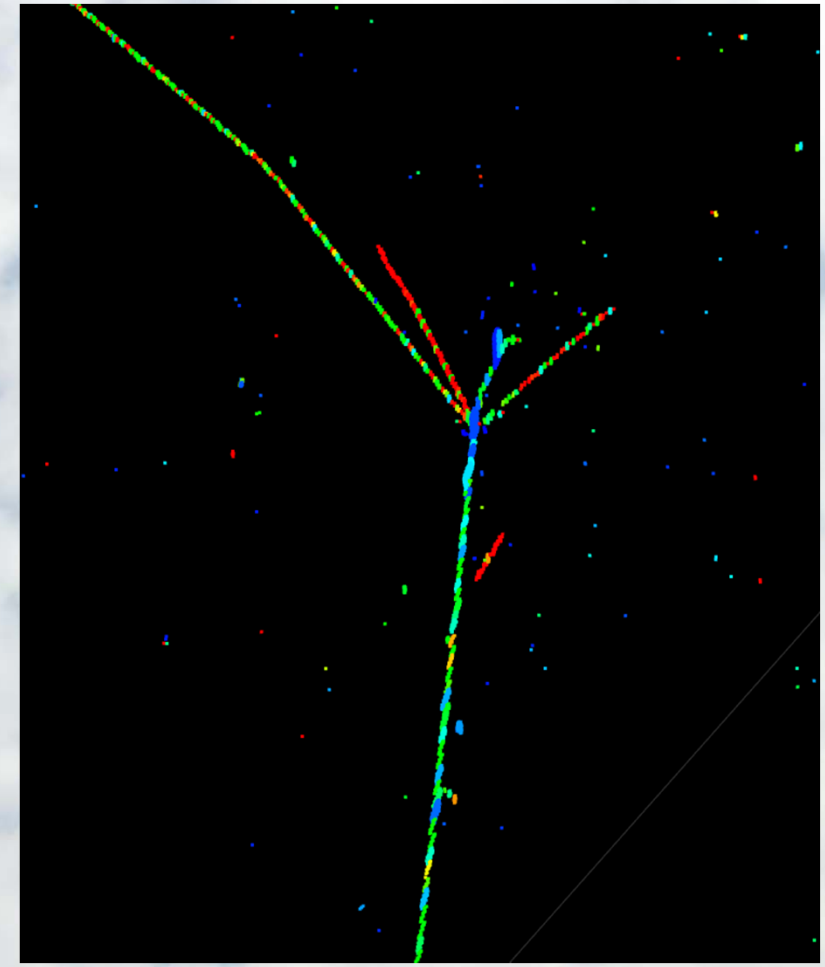
First proposed by C. Rubbia, **1977** → **ICARUS**;

For 3D demo, visit http://www.phy.bnl.gov/wire-cell/examples/mvd/nue-cc-v2/#/1

Electron Shower



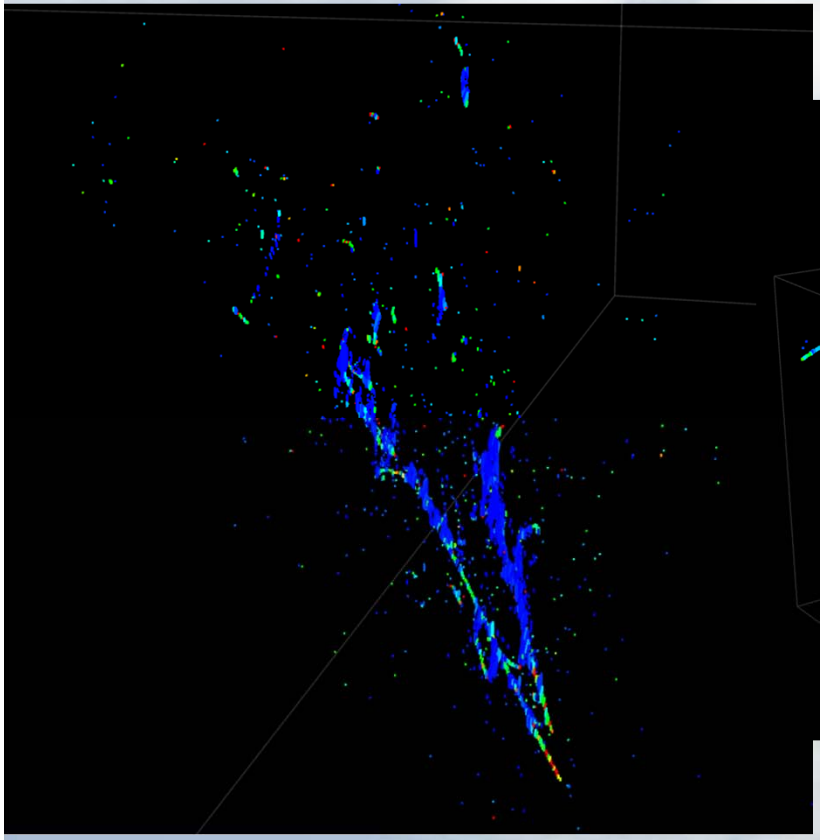
Hadronic Shower



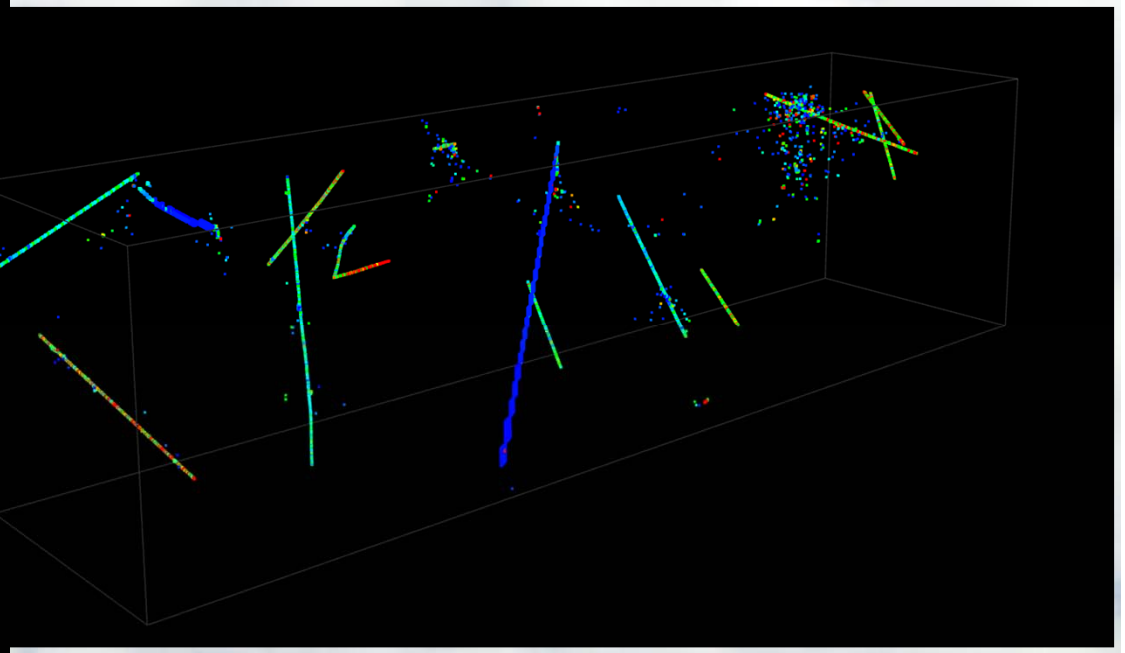
For 3D demo, visit

http://www.phy.bnl.gov/wire-cell/examples/list/

Neutral pion



Neutrino interaction buried under cosmics



Periodic Summary

- To find the origin of matter-anti-matter asymmetry, we decide to look at the neutrino sector
- With all available channels and practical constraints, we decide to search for new CP violation

$$\text{CP-violation:} \quad P\left(\nu_\mu \rightarrow \nu_e\right) \neq P\left(\bar{\nu}_\mu \rightarrow \bar{\nu}_e\right)$$

- Is this approach viable?

Yes, θ_{13} is non-zero ~ 8.4°

- What about the detector technology?

LArTPC is a very promising, but complicated detector technology.
It is crucial to gradually scale up and practice this new technology → MicroBooNE an 80 tons LArTPC

Fermilab's Booster Neutrino Beam (BNB)

Linac
Length: 150m
Proton Energy: 400 MeV

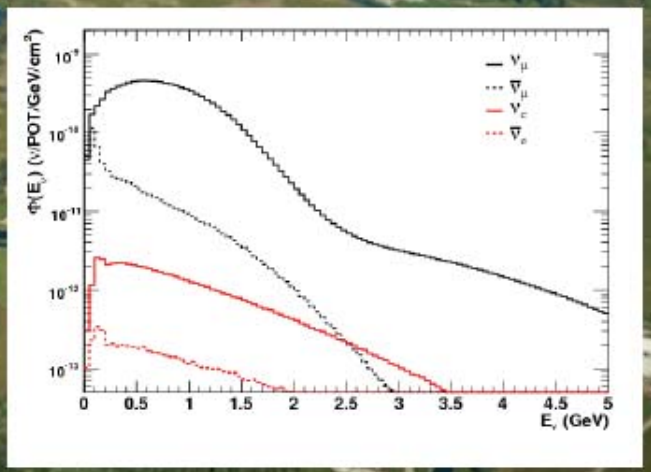
Booster
Circumference: 468m
Proton Energy: 8 GeV

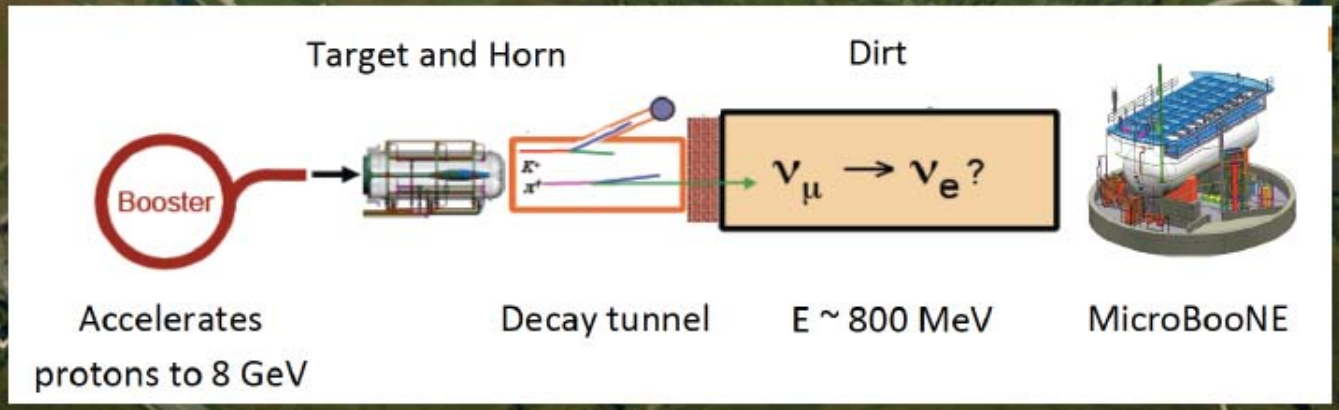
Protons

Neutrinos

MicroBooNE detector

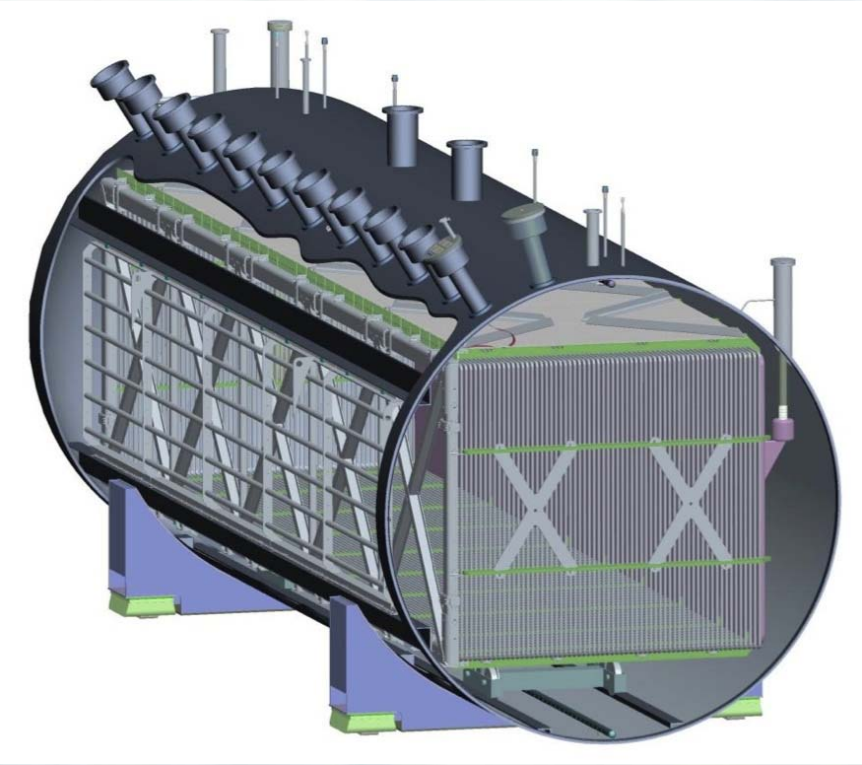
Fermilab's **low-energy** neutrino beam
<Eν> ≈ 700 MeV





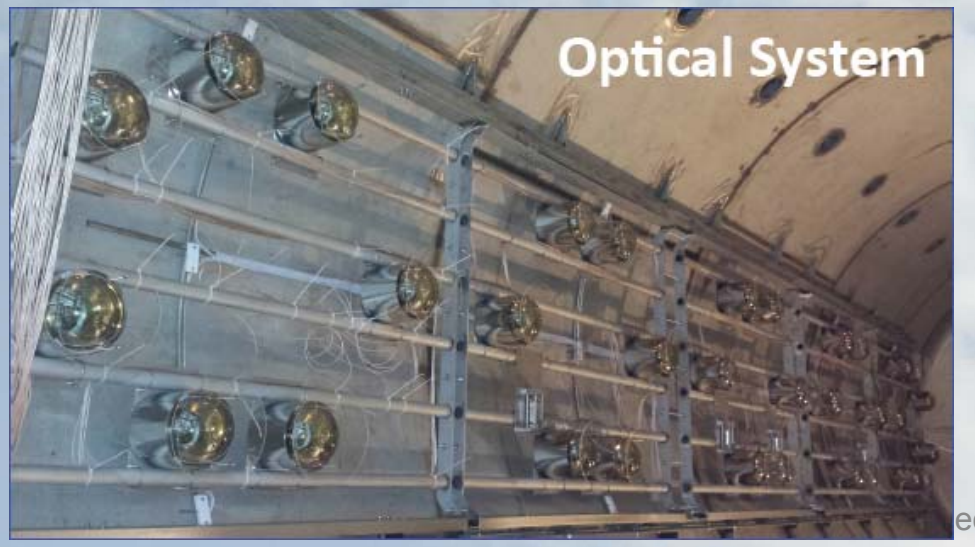
MicroBooNE LArTPC

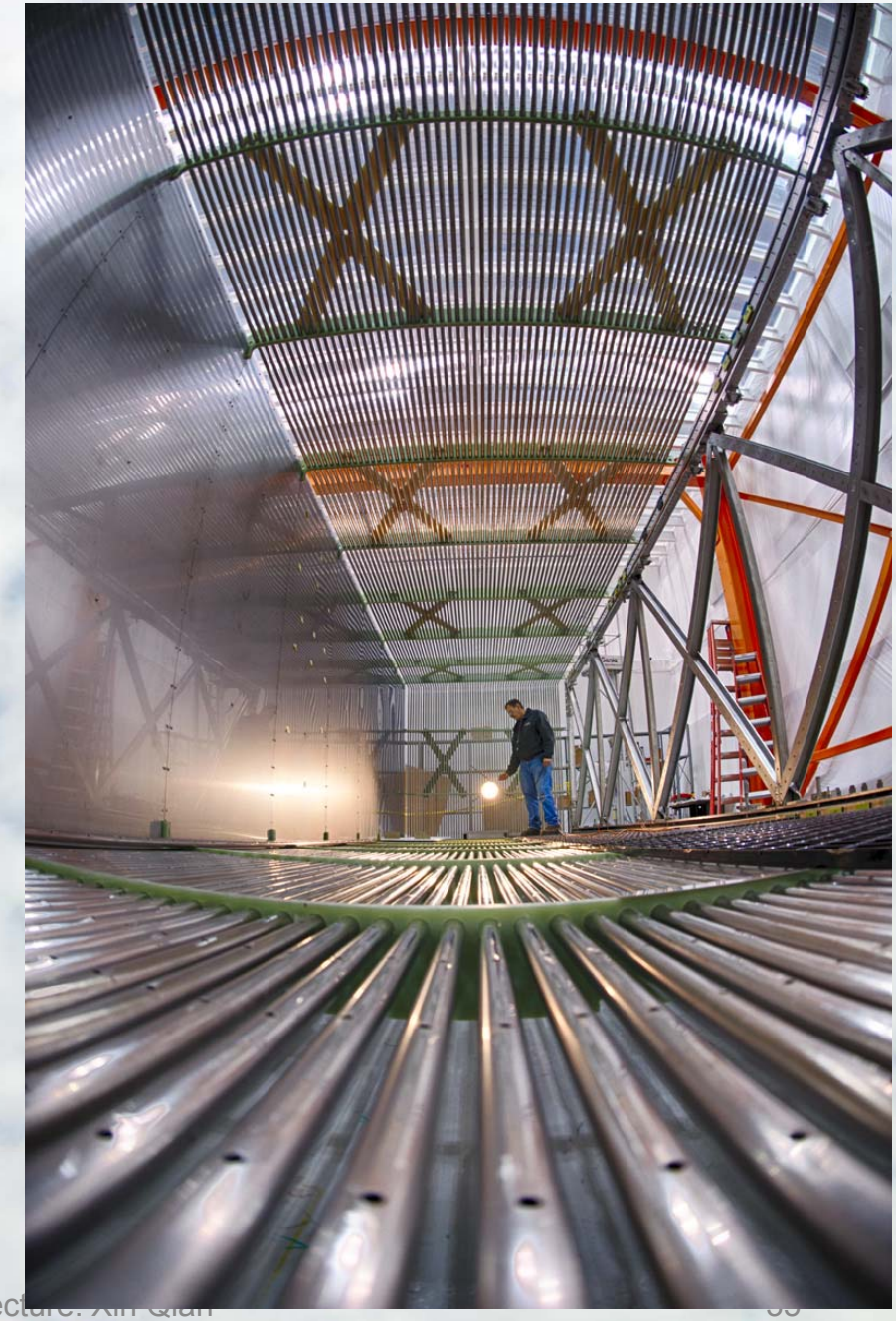
- Time Projection Chamber
  - 3 wire planes
  - 8256 channels
  - 1.6 ms drift time
- Optical system
  - 32 cryogenic PMTs
- Laser-based Calibration System
- High Voltage System
- Many innovative technologies

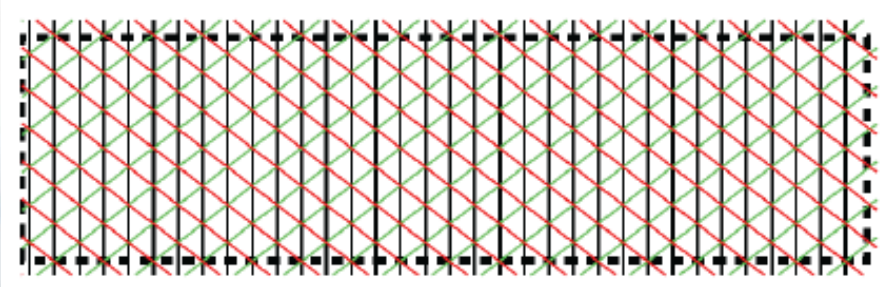


10.3 x 2.3 x 2.5 m
Uniform field of 500 V/cm
170 tons of purified LAr

Cryostat


Optical System





Moving day!

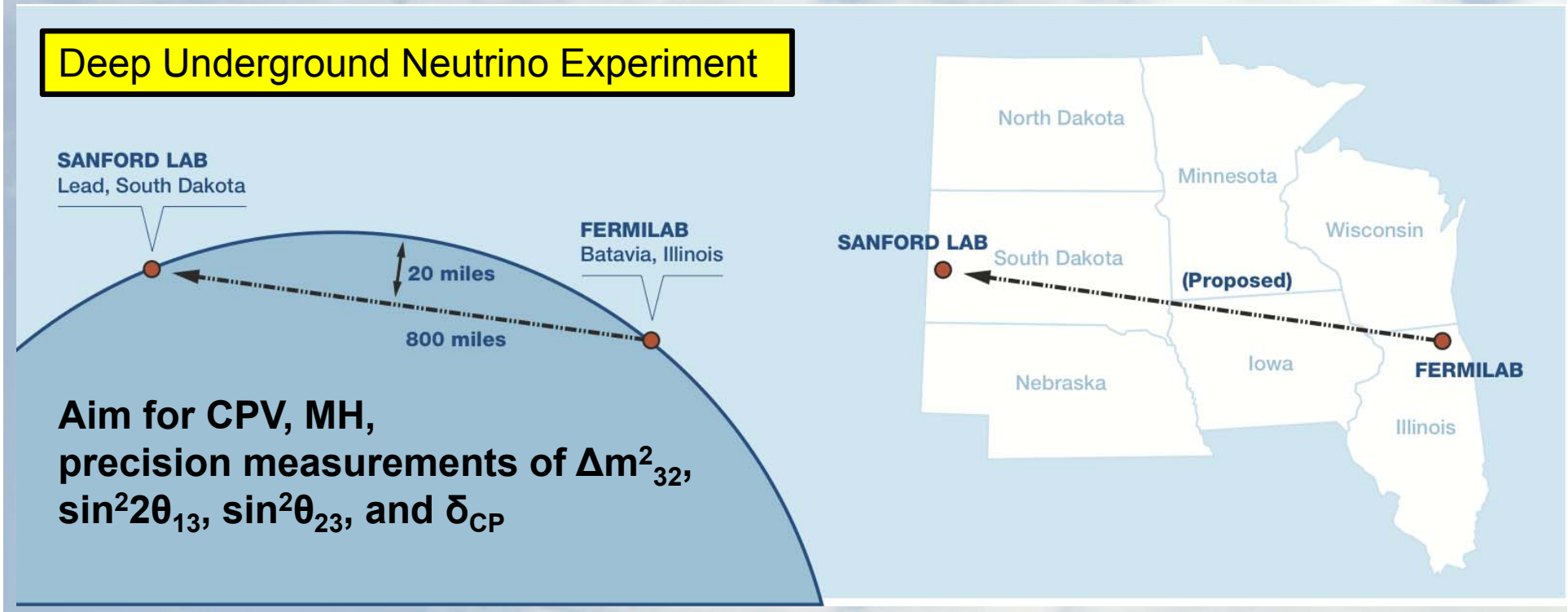
June 23rd, 2014

Data is coming!

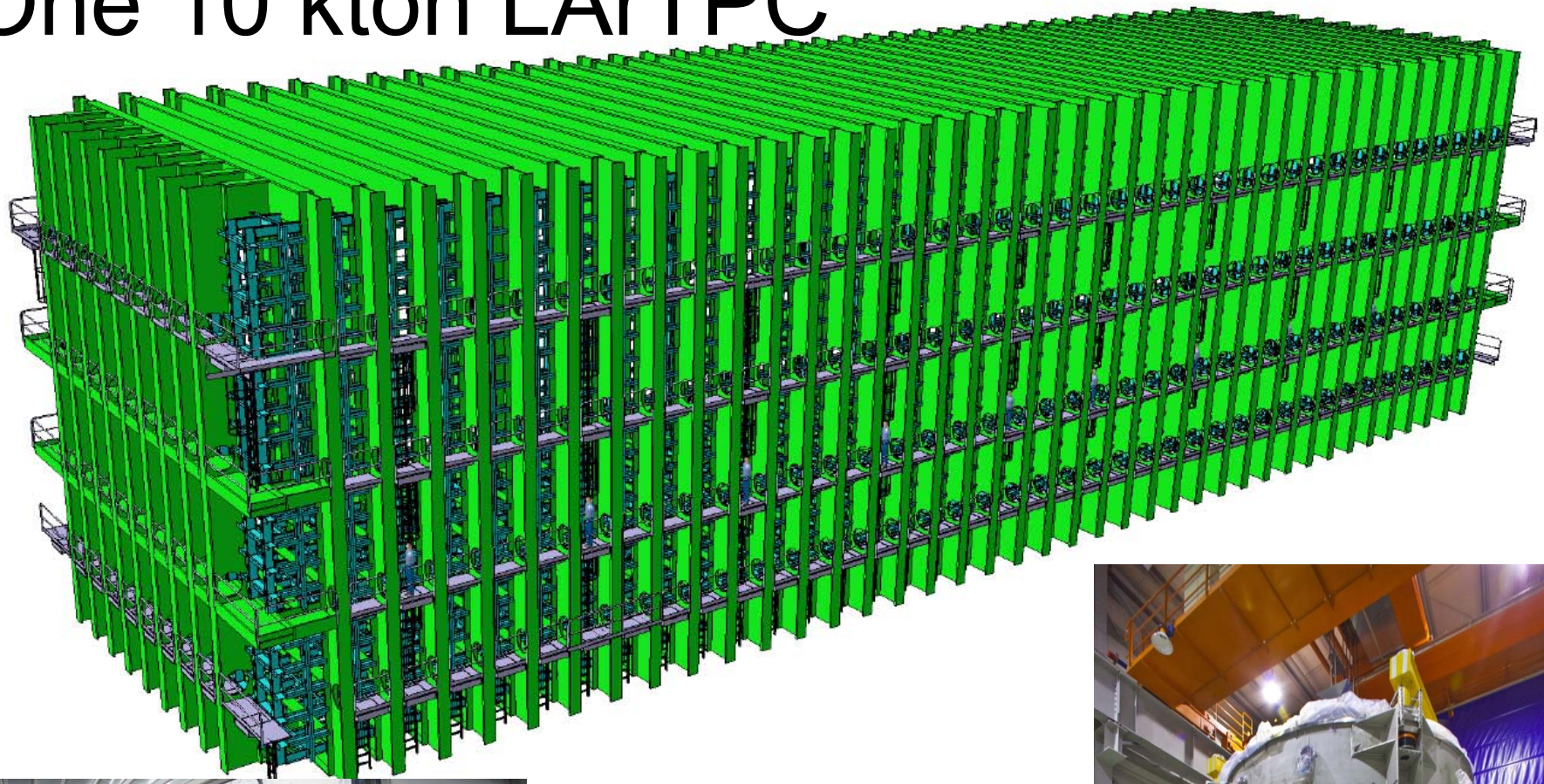
The Experimental Design and Future Challenges

Deep Underground Neutrino Experiment

- A horn-produced broad band beam with 60-120 GeV protons at 1200 kW (upgradable to 2.3 MW) from FNAL
- A baseline of 1300 km towards the Sanford Underground Research Facility in Lead, South Dakota
- A 40 kt fiducial volume Liquid Argon Time Projection Chamber located at the 4850 ft level
- A high resolution near detector at FNAL
- This configuration will be achieved in phases according to $ constraints



One 10 kton LArTPC



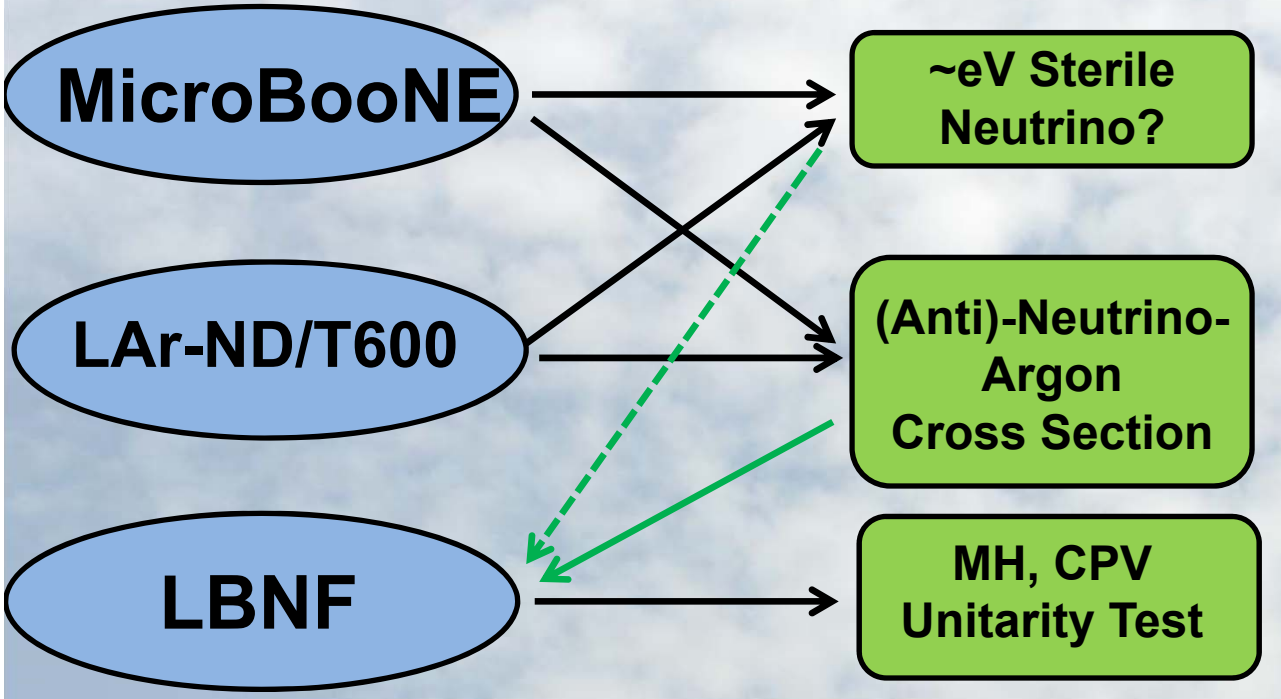
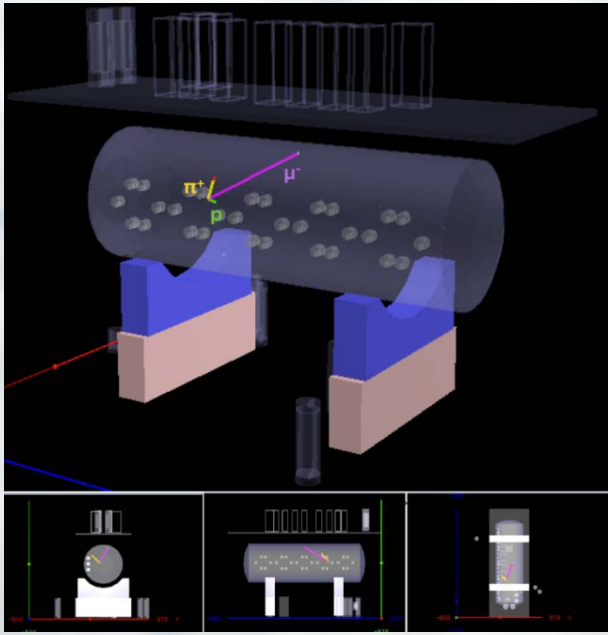
There are many challenges ahead

- How to scale up the detector to 40 kt?
- How to achieve high purity argon at this scale?
- How to properly reconstruct neutrino interaction events to maximize the potential of this technology?
- How to properly control the systematics for precision measurements?
- How to collect enough resources for construction?
- How to maintain a healthy field with such a long-term project?
- …

Summary

- We are lucky that θ_{13} is non-zero
- LArTPC technology is promising and under healthy development
- Design of next-generation long-baseline accelerator neutrino experiment is sound
- It has been a long journey to search for new CP violation to explain why we are made of matter
- Our patience will be rewarded, exciting decades to come!

In Memorium

Aditya Sambamurti
1961-1992

Physics Program Of MicroBooNE